University of Alberta

Fueling Dreams of Grandeur: Fuel Cell Research and Development and the Pursuit of the Technological Panacea, 1940-2005

by

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Abstract

The record of fuel cell research and development is one of the great enigmas in the history of science and technology. For years, this electrochemical power source, which combines hydrogen and oxygen to produce electricity and waste water, excited the imaginations of researchers in many countries. Because fuel cells directly convert chemical into electrical energy, people have long believed them exempt from the so-called Carnot cycle limitation on heat engines, which dictates that such devices must operate at less than 100 per cent efficiency owing to the randomization of energy as heat. Fuel cells have thus struck some scientists and engineers as the "magic bullet" of energy technologies.

This dissertation explores why people have not been able to develop a cheap, durable commercial fuel cell despite more than 50 years of concerted effort since the end of Second World War. I argue this is so mainly because expectations have always been higher than the knowledge base. I investigate fuel cell research and development communities as central nodes of expectation generation. They have functioned as a nexus where the physical realities of fuel cell technology meet external factors, those political, economic and cultural pressures that create a "need" for a "miracle" power source. The unique economic exigencies of these communities have shaped distinct material practices that have done much to inform popular ideas of the capabilities of fuel cell technology.

After the Second World War, the fuel cell was relatively unknown in industrial and governmental science and technology circles. Researchers in most leading industrialized countries, above all the United States, sought to raise the technology's

profile through dramatic demonstrations in reductive circumstances, employing notional fuel cells using pure hydrogen and oxygen. Researchers paid less attention to cost and durability, concentrating on increasing power output, a criterion that could be met relatively easily in controlled conditions. While such demonstrations typically led to short-term investments in further research, they also generated expectations for long-lived and affordable fuel cells using hydrocarbons. However, developing commercial fuel cell technology was an expensive and arduous process, one that few sponsors were willing to support for long in the absence of rapid progress. Despite this mixed record, the fuel cell has become a powerful symbol of technological perfection that continues to inspire further research and dreams of energy plenitude.

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Glossary

Alkaline fuel cell: a fuel cell employing an alkaline electrolyte, usually potassium hydroxide, and operating at around 200°C.

Anode: the negatively charged electrode in a primary or fuel cell battery, the location of the de-electronation reaction in which a fuel substance is ionized, or stripped of electrons, which then enter into a circuit. In an electrolysis cell, the anode is the positive electrode.

ARPA: Advanced Research Projects Agency. Created in 1958, this government agency sponsored defense-related basic research in the U.S.

Cathode: the positively charged electrode in a primary or fuel cell battery, the location of the electronation reaction in which electrons released at the anode move through an external circuit. In an electrolysis cell, the cathode is the negative electrode.

Catalyst: a substance that changes or accelerates a chemical reaction that is not itself permanently changed by the reaction.

Current: the quantity of charge carriers (electrons or de-electronated atoms) that flow past a point in an electric circuit in a given time: the International System of Units (SI) unit of electric current is the ampere; an ampere is equal to the flow of one coulomb of charge per second.

Current density: current per area or the rate of an electrochemical reaction; typically measured in milliamperes per square centimeter or amperes per square meter.

Direct fuel cell: usually refers to a fuel cell system using a fuel that is directly introduced into the operating system with no prior processing. The term may refer to a hydrogen fuel cell but is generally understood to refer to a fuel cell that uses carbonaceous or hydrocarbon fuel that has not been converted into a hydrogen-rich gas.

DSIR: Department of Scientific and Industrial Research. Established by the British government in 1915-1916, this funding agency supported academic scientific research and education as well as industrial research.

Electro-oxidation: the ionization of hydrogen atoms and their combination with oxygen molecules in a fuel cell or battery, liberating electrons and producing waste water.

Electrolyte: a chemical solid or liquid that conducts an electric current via ions moving in an electric field between electrodes in a battery or fuel cell.

Energy density: the measure of the capacity of conventional galvanic batteries to store electricity relative to their volume and supply it for a given period of time. This is typically expressed in terms of watt-hours per liter.

ERA: Electrical Research Association. A British industrial cooperative research organization founded in 1920.

Fuel cell stack: a number of individual fuel cells clustered together to form an array. Within fuel cell communities, the term "stack" is preferred over "battery" to distinguish full-sized fuel cells from conventional galvanic batteries.

HFI: Hydrogen Fuel Initative. Hydrogen fuel infrastructure program introduced by the Bush administration in 2003.

IDA: Institute for Defense Analyses. Established in 1954 to supply systems analysis to the U.S. defense research and development community.

Indirect fuel cell: refers to a fuel cell system coupled with a fuel reformer that converts a carbonaceous or hydrocarbon fuel into a hydrogen-rich fuel gas, which is then fed into the fuel cell.

Invariance: an idealized state of chemical stability or equilibrium within a fuel cell stack such that no destructive side reactions occur that would degrade electrodes, pollute electrolytes and shorten the lifespan of the power unit.

NRDC: National Research Development Corportion. Established in Britain in 1948, the NRDC was designed to exploit innovations developed with public funds.

PAFC: Phosphoric acid fuel cell. A fuel cell employing liquid phosphoric acid electrolyte and operating at moderate temperature, above 200°C.

Parallel connection: a battery or fuel cell array in which like terminals in each successive cell are electrically linked (anode to anode, cathode to cathode).

PEM: Proton exchange membrane fuel cell. A fuel cell employing a solid polymer electrolyte, typically acidic, and operating at relatively low temperatures, around 85°C.

Power density: rate of power flow in a specific direction at a particular point in a transmission medium. Because fuel cells have no intrinsic storage capacity, power density, not energy density, is the main criterion of their efficacy. Unlike energy density, power density is not expressed as a time relationship, but rather in terms of watts or kilowatts per unit of weight or volume (kilogram or liter). In electrical systems, power is a product of current, the rate at which charge flows past a point, and voltage, or electromotive force.

PNGV: Partnership for a New Generation of Vehicles. Introduced by the Clinton administration in 1993, this research and development program focused on improving the fuel efficiency of internal combustion engine-powered automobiles.

Reformer: a device that converts a carbonaceous fuel to hydrogen-rich fuel gas.

Series connection: a battery or fuel cell array in which unlike terminals of each successive cell are connected together (cathode to anode).

Voltage: electromotive force or the strength of electric pressure, measured in volts or joules per coulomb. Voltage is the quantitative expression of potential difference in charge between two points in an electric field. The greater the voltage, the greater the flow of electric current. In fuel cells, voltage and efficiency decrease as current density and power increases until at very high current density, power and voltage rapidly drop to zero. As a result, fuel cells operate at relatively low voltages compared to conventional batteries.

Watt: International System of Units (SI) unit of power; the rate at which work is done or the rate at which energy is expended. One watt is equivalent to one joule of work per second.

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Introduction

In 1960, eight students at Harvard University's Graduate School of Business published an analysis of the technical and economic feasibility of fuel cells, a technology that silently converts chemical into electrical energy by reacting hydrogen with oxygen, producing water as waste. The preface to their 160-page study purposely featured selections from the 1875 edition of the *Congressional Record* heralding the era of the gasoline-powered internal combustion engine. This technology, the *Record* declared, would begin a "new era in the history of civilization," one potentially more revolutionary than the "invention of the wheel, the use of metals, or the steam engine." Developing and adopting the new fuel/propulsion technology, the 1875 extract stated, would present major cost and technical challenges and introduce considerable socio-economic dislocation. Gasoline was a dangerous and dirty fuel. Vehicles powered by it could attain high speeds, threatening hapless pedestrians, fouling the air, and displacing horse power on farms, ruining American agriculture. But in the late nineteenth century, the gasoline engine was a technology that was also "full of promise for the future of man and the peace of the world."[1]

The object of the Harvard graduates in choosing this selection to frame their appeal was unmistakable. Eighty-five years after gasoline engines first challenged and then irrevocably altered the established socio-technical order, they suggested, a new technology was poised to upset the status quo and bring about a new energy-transport paradigm. Then, as now, developing and marketing new technologies brought potential risks and rewards. However, the graduates implied, the lessons of history were clear.

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[1] David R. Adams et al., *Fuel Cells: Power for the Future* (Cambridge, MA: Fuel Cell Research Associates, 1960), 9. The extract did not specify how motorization would spoil American agriculture.

For years following its invention in the mid-nineteenth century, this electrochemical power source excited imaginations. Researchers long believed it had the potential to be more efficient than the heat engine, which converts chemical energy into heat energy and uses the resulting kinetic motion of molecules in a hot gas to drive a mechanical device such as a piston or turbine. In 1824, the French scientist Sadi Carnot developed a theory of thermodynamics which held that there could not be a perfectly efficient heat engine because such devices must lose a portion of their energy as heat exhaust. But because fuel cells directly convert chemical into electrical energy and do not randomize energy as heat in the manner of a heat engine, researchers assumed they were exempt from the Carnot limitation on efficiency. As a result, scientists and engineers have perceived fuel cells as the "magic bullet" of power technologies. After the Second World War, private companies and governments spent billions of dollars trying to develop a long-lasting and affordable commercial fuel cell. Yet these hopes have been perennially dashed as expectations outpaced the knowledge base.

The fuel cell concept was developed in the mid-nineteenth century when a handful of European researchers began to experiment with reversing the electrolysis phenomenon. Instead of using electricity to dissociate water into hydrogen and oxygen, they attempted to combine oxygen and hydrogen to produce electricity. In 1839, the British lawyer and amateur scientist William Grove and the Swiss physicist Christian Friedrich Schoenbein used platinum foil to catalyze a reaction between hydrogen and oxygen. Grove further elucidated the chemical basis of this reaction in subsequent experiments published in 1843 and 1845.

Little more was done until the 1890s, when European scientists revived the concept in a new series of experiments using coal and coal-derived gases as a source of hydrogen. To chemical and electrochemical experts, it seemed as if the fuel cell had the potential to replace the dominant internal combustion engine technology. The German physical chemist Wilhelm Ostwald exemplified these hopes in a passionate address before a group of engineers in 1894. He invoked the idea of direct electrochemical conversion of solid coal to electricity as a possible replacement for the steam engine, a technology Ostwald saw as "incomplete" because it converted only a fraction of the energy in coal to useful work and the rest to waste heat, soot and smog.[2] While a number of these electrochemical energy conversion devices were built in the late nineteenth and early twentieth centuries, none approached the durability or cost-effectiveness of conventional batteries or heat engines. In 1939, the German researcher Emil Baur remarked how strange it was that advances in fuel cell theory and the state of the technological art made in the 1890s had borne no fruit almost a half century later.[3]

Hopes were rekindled in the late 1950s and early 1960s when the first practical fuel cells were developed in Britain and the United States. Researchers then believed these devices were capable of overcoming the limitations of existing storage battery technology. The differences between these power sources are relatively simple but important and will shortly be examined in detail. For now, the key point to understand is that in conventional storage batteries, the electrodes are also the "fuel," and are thus gradually consumed over time; in contrast, fuel cells use chemical reactants that are stored externally, not within the battery casing itself. This has caused researchers to reason that as long as fuel was supplied, fuel cell electrodes and electrolyte would continue to operate with no chemical deterioration, a state known as "invariance." Thus, at first sight, fuel cells seemed a solution to limited storage capacity, the main handicap of conventional batteries.

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[2] Wolf Vielstich, Arnold Lamm and Hubert A. Gasteiger eds., "Part 4: Fuel Cell Principles, Systems and Applications," in *Handbook of Fuel Cells: Fundamentals, Technology and Applications; Volume I: Fundamentals and Survey of Systems* (Chichester, UK: John Wiley and Sons, Ltd., 2003), 161-162.
[3] Emil Baur, *Bulletin Schweitz ETV* 30, 17 (1939): 478.

Beginning in the early 1960s, the United States federal government began developing fuel cells for military and quasi-military purposes in both terrestrial and aerospace applications. A variety of industries also made large investments in hopes of bringing cheap and durable fuel cells to market. By the early 1970s, most had abandoned this work as costs and technical problems mounted. More than half a century again after Baur's observation and twenty years after the first post-war flurry of excitement and investment in fuel cells, another wave of optimism rose in the early 1990s. This time, expectations were greater than ever. The automobile industry, the Department of Energy and, by the early 2000s, the White House, saw the electric passenger vehicle as the most desirable application of fuel cell power. They believed the mass-produced fuel cell electric automobile could solve the environmental and geopolitical problems caused by the dependence on fossil-fuelled internal combustion engine transportation.

By the turn of the millennium, the sponsors of fuel cell research and development had apotheosized the technology. Enthusiastic projections by engineers, media pundits and politicians of the imminent mass commercialization of fuel cell automobiles became leavened with truly utopian rhetoric framing the fuel cell as the basis of the "hydrogen economy," a revolutionary new energy order that would sweep away the old energy and transportation system. These expectations, too, went unfulfilled. The auto industry's forecasts of imminent mass production of fuel cell vehicles gave way to revised timelines, increased skepticism and eventual withdrawal of capital as sponsors encountered what they perceived to be crippling technical and economic obstacles.

In this dissertation, I explore the reasons why expectations for a commercial fuel cell have been so consistently unrealistic and unrealized, a record perhaps unique in the annals of modern technology and one that remains unexplained by extant scholarship. I focus on the legacy of applied research and development. While historians and sociologists have lain to rest generalized linear notions of technological development in which "research" must precede "development," this idea remains deeply embedded in society. Once more, we encounter this assumption in the history of fuel cells. My work contributes to this scholarly critique, showing that efforts to apply basic knowledge in fuel cell technology have often become renewed searches for basic physical principles. The history of fuel cell research and development is one of progress in some areas neutralized by crippling new difficulties in others.

I also investigate the recent popular idealization of the fuel cell as a "miracle" battery. As a novel power source that may be used in a wide variety of electrical storage and production applications including radios, radars, spacecraft, automobiles and distributed and central electricity generation plants, fuel cells have been all things to all people. In the last 20 years, the idea that fuel cells would allow the reconciliation of our taste for modern consumer products with our desire for a clean environment has become powerfully attractive to groups from across the ideological spectrum. The efforts of environmentalists and the business community to use fuel cell technology to serve quite disparate socio-economic and political ends reveals the depth of the affinity for technological utopianism in American culture.

Historiography

There has been almost no scholarly work on the history of fuel cell research and development, though there is a wealth of technical and archival material and scores of handbooks, manuals and conference proceedings. The authors of such works, many of whom are engineers and technicians who were or are actively engaged in research, often express concern with the technology's unusual past and, sometimes, incredulity that it has not yet been commercialized. Perhaps not surprisingly, they generally treat the history of fuel cells as an afterthought, confining it to subsections or appendices. These researchers are concerned with the future, not the past, and regard fuel cell research and development as an ongoing saga that will one day be crowned with success. In rationalizing "failure," these sources tend to focus on what they consider "objective" technical factors, such as expensive materials or faulty design. This is the approach taken by A.J. Appleby and F.R. Foulkes in their *Fuel Cell Handbook*, widely considered to be the authoritative account of fuel cell technology.[4]

The French sociologist Michel Callon was the first scholar to conduct a serious socio-political analysis of fuel cells. In the 1980s, he wrote several essays on the origins of the French electric car programs of the 1960s and 1970s in which he briefly addressed fuel cell development. His primary concern was how the politics of research and development, particularly the role of state intervention, gave rise to new technologies. The genesis of the French electric car program served to illustrate how alliances between government, industry and academe helped shape science and technology policy. As British and American demonstrations of fuel cell prototypes excited worldwide interest in the late 1950s and early 1960s, French scientists, policy analysts, industrial researchers and the state electrical utility believed a "technological revolution" was in the making. Each group saw a fuel cell program as a way to achieve parochial objectives. For patriotic science and technology planners, it would help bridge theory and technique, enhancing national prestige through the expansion and enrichment of the field of electrochemistry. The politically powerful electrical utility became involved mainly to support its dream of developing a commercial electric vehicle. As a result, the program concentrated on a small fuel cell suitable for an automobile rather than a large one that could be used as a generator, a technology the utility believed could be used to undermine its monopoly on the production and distribution of electricity.[5]

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[4] A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), viii.

Callon raised general points relevant to the rise of postwar fuel cell research and development. The most important is the impression early British and American projects had on French science and technology elites and the forging of broad fuel cell coalitions in which "everyone's interests were taken care of," a process that involved simplifying the technical issues at stake. Callon was less interested in the origins of the "technological revolution" or the conduct of fuel cell research and development within the laboratory, especially the dynamics of simplification and how they related to alliance building and the generation of expectations and enthusiasm.[6]

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[5] Michel Callon, "The State and Technical Innovation: A Case Study of the Electric Vehicle in France," *Research Policy* 9 (1980): 362-366.

Gerrit Jan Schaeffer's unpublished doctoral dissertation is one of the few other notable studies of fuel cell research and development. Viewing this history as a sequence of "contingent and dramatic episodes," Schaeffer focused on European fuel cell programs, recapitulating some of Callon's original case studies in more detail. Like Callon, Schaeffer traced expectations that triggered European research programs to demonstrations staged in 1959 by British and American researchers. And like Callon, Schaeffer did not relate these case studies to the larger history of post-Second World War fuel cell research.[7] This is an important omission, for the United States has devoted more resources to developing fuel cells than any other country. Schaeffer also had little to say about Francis Thomas Bacon, the English mechanical engineer whose fuel cell he acknowledges played an important role in informing expectations in the pivotal year of 1959. Finally, Schaeffer attributed the persistence of post-war fuel cell research and development to the sheer number of programs and volume of scientific papers and demonstrations; these, he claims, attracted a continual stream of new players to the field.[8] However, this tautology revealed little of the motives of researchers and sponsors in pursuing fuel cell development and the ways in which expectations were generated.

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[6] Callon, "The Sociology of an Actor-Network: The Case of the Electric Vehicle," in *Mapping the Dynamics of Science and Technology: Sociology of Science in the Real World*, eds. Michel Callon, John Law and Arie Rip (London: Macmillan Press, 1986), 29-31. Callon's primary objective was to use French fuel cell research and development as a case study to help illustrate the so-called "actor-network" theory of power relations in science and technology communities. He elucidated the role of technological simplification as a key element of coalition-building more than seven years after he first began examining French fuel cell communities. Callon held that diverse coalitions supporting fuel cell research formed only after the relevant technical issues had been simplified. He suggested that such coalitions weaken once the true degree of electrochemical complexity in fuel cell development becomes apparent to the respective parties.

[7] Gerrit Jan Schaeffer, *Fuel Cells for the Future: A Contribution to Technology Forecasting From a Technology Dynamics Perspective* (Ph.D diss., University of Twente, 1998), 19, 155.

[8] Ibid., 181.

These approaches suffer from a tendency towards sweeping and sometimes untenable generalization symptomatic of a failure to account for historical change, problems common to many sociological treatments of science and technology.[9] Any comprehensive study of fuel cell research and development must, however, be rooted in the history of industrial research in general and in industrial laboratories in particular, for it was in that context, with a few important exceptions, that the vast majority of the work on fuel cells was done after the Second World War. My own work, then, explores the material practices of fuel cell research and development communities in industrial laboratories in Britain and the United States, the leading fuel cell nations, from the 1940s to the mid-2000s.

There are a number of outstanding issues in the historiography of industrial research that bear upon the history of fuel cells and fuel cell research and development in important ways. These include the processes by which people have conceptualized the interaction between science and technology and particularly the ways they have defined the role of "pure science" in this relationship. These problems coalesce in the so-called "linear model" of innovation, a concept that poses knotty epistemological and ontological problems. The historian of science and technology David Edgerton notes that the linear model refers to a belief in the origin, process and effects of innovation; "pure" or "basic" science is the source of innovation, which unfolds sequentially, with scientific discoveries informing "applied" research that, in turn, leads to the production of technology.[10] The linear model has frequently been associated with work practices in the first industrial laboratories that emerged in the early twentieth century, above all with the novel institutional structure some scholars have referred to as the "golden triangle." This describes the close partnership between military agencies, industrial laboratories and universities.[11] Though fuel cell research and development occurred largely within industrial laboratories, these were nevertheless firmly rooted in post-war golden triangle structures both in Britain and the United States, hosting a form of research that was fundamentally interdisciplinary and which maintained important links with universities and a variety of government agencies.

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[9] Michael Aaron Dennis, "Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science," *Social Studies of Science* 17 (1987): 481.

Historians of technology generally concur that the "linear model" does not accurately describe the actual course of technology development at any stage of history, observing that the science-technology relationship has been much more complex. Michael Aaron Dennis, for example, has argued that it becomes pointless to distinguish "where science ends and technology begins, or vice versa," given the increased use of technological instruments to produce scientific knowledge from at least the nineteenth century onwards, as well as the more recent trend of workers in modern industrial laboratories employing scientific methodology to understand the physical principles of technology.[12]

There is also little dispute that the linear model was invoked by a relatively small but influential group of academic scientists and engineers in Britain and the U.S, most notably the Massachusetts Institute of Technology engineering professor Vannevar Bush, as a means of leveraging increased government support for basic science after the Second World War.[13] It was further popularized by politicians and the media, becoming part of the popular consciousness. The ideological, institutional and technological consequences of linear thinking, however, are less clear. Noting that a formal linear model has never been drafted by science and technology policy elites, Edgerton reasons that the concept was wholly the creation of academics, who preferred setting it up as a "straw man" to a more incisive investigation of the nature of technological innovation. For him, the effects of the linear model, uniformly negative, have been restricted almost entirely to the realm of historical and sociological studies of science and technology.[14]

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[10] David Edgerton, "'The Linear Model Did Not Exist:' Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century," *The Science-Industry Nexus: History, Policy, Implications*, eds. Karl Grandin, Nina Wormbs and Sven Widmalm (Sagamore Beach, MA: Science History Publications/USA 2004), 32.

[11] Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993), 2.

[12] Dennis, "Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science," 490.

A more widespread view, articulated by Harvey Brooks, is that *belief* in the linear model has had a pervasive and lasting effect on the organization and planning of technology development in the West.[15] Science and technology policy planners may never have developed a formal linear model, but, steeped as they were in its ideology, they tried to apply linear modes of management to inherently non-linear processes of science-based technology development, with important consequences for the conduct of research and development. Glen R. Asner demonstrates this in his examination of the Department of Defense's so-called Independent Research and Development program. Launched in 1959, it massively increased funding for undirected basic research in industrial laboratories. In an effort to reassert managerial control over weapons development programs, the Pentagon strictly defined "basic research," "applied research" and "development," linking them sequentially as a prescribed mode of technology innovation and requiring that contractors separately account for their research and development costs. This led many to restructure their weapons development along linear lines, physically isolating research, development and manufacturing.[16]

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[13] The science journalist Daniel S. Greenberg was one the earliest critics of both this trend and the linear model; see *The Politics of Pure Science*, new ed. (Chicago: The University of Chicago Press, 1999), 29-31.

[14] Edgerton, "'The Linear Model Did Not Exist:' Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century," 31-34.

[15] Harvey Brooks, "The Evolution of U.S. Science Policy," in *Technology, R&D, and the Economy*, eds. Bruce L.R. Smith and Claude E. Barfield (Washington, D.C: The Brookings Institution and American Enterprise Institute, 1996), 21. For works that address the influence of linear thinking in the politics, practice and organization of science and technology, see David Edgerton's *Science, Technology and the British Industrial 'Decline,' 1870-1970* (1996), Daniel S. Greenberg's *The Politics of Pure* Science (1966) and *Science, Money and Politics: Political Triumph and Ethical Erosion* (2001), David Hounshell and John Kenley Smith's *Science and Corporate Strategy: DuPont R&D, 1902-1980* (1988) and Daniel Kevles' *The Physicists: The History of A Scientific Community* (1971) and "K1S2: Korea, Science, and the State," in *Big Science: The Growth of Large-Scale Research* (1992).

Theoretical Frame and Methodology

Where the historical analysis of technological innovation in industrial laboratories in golden triangle relationships is concerned, then, the problem of where science stops and technology begins is not "pointless" but is rather the main point. It begs the question of how interdisciplinary work processes within these environments were classified, funded, managed and shaped or otherwise altered by their government sponsors. I adopt and expand Asner's model of technology development as the fundamental theoretical frame for understanding the history of fuel cell research and development. As I shall demonstrate, while the structure of British and American fuel cell golden triangles differed significantly, their managers shared similar assumptions of technological progress. Both attempted to impose linear management protocols on the non-linear interdisciplinary practices of fuel cell laboratories, with important consequences for the epistemology and conduct of research and development and for the configuration of the technological products. Consequently, the terms "basic research," "applied research" and "development" in the history of fuel cell research and development cannot be treated as absolutes: they have meant different things to different actors at the same time, or different things to the same actor at different times.

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[16] Glen R. Asner, "The Linear Model, the U.S. Department of Defense and the Golden Age of Industrial Research," *The Science-Industry Nexus: History, Policy, Implications*, eds. Karl Grandin, Nina Wormbs and Sven Widmalm (Sagamore Beach, MA: Science History Publications/USA, 2004), 3-12.

In developing my analysis, I also draw from themes in business and economic history and from various sub-disciplines in the history and sociology of science and technology. While sociologists and historians have generally concentrated on "success" stories, they have paid more attention in the last 20 years to the "losers" of history. In the technological context, success and failure are relative terms; some literature focuses on technologies that have failed with literally catastrophic results, as in the collapse of a bridge or building or crash of a vehicle of some kind.[17] Other work explores technologies that have "died out" or remained marginal in society, typically in relation to devices that have "succeeded." This includes almost every imaginable sort of artifact including household appliances, computers, machine tools, a wide variety of vehicles and batteries in certain applications, to name only a few.[18]

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[17] For example, see Henry Petroski's *Success Through Failure: The Paradox of Design* (2006), *Design Paradigms: Case Histories of Error and Judgment In Engineering* (1994), *To Engineer is Human: The Role of Failure in Successful Design* (1992), Harry Collins and Trevor Pinch's *The Golem at Large: What You Should Know About Technology* (1998) and Charles Perrow's *Normal Accidents: Living With High-Risk Technologies* (1984).

[18] See, respectively, Ruth Schwartz Cowan's *More Work for Mother: The Ironies of Household Technology From the Open Hearth to the Microwave* (1983), Paul Ceruzzi's *A History of Modern*

The history of fuel cell development most resembles the latter of these cases, for reasons I will later outline. While catastrophic failures of fuel cells have commonly occurred during laboratory tests, practical fuel cell power plants have performed reliably enough in certain roles. Developers have achieved success with highly specialized and costly fuel cells in niche roles, particularly in the U.S. space program. As we have seen, however, plans to commercialize fuel cells on a large scale, let alone grand schemes of a whole new energy system based on widely available commercial fuel cells, have not come to fruition.

I also employ methodology from the branch of the history and sociology of technology that focuses on the construction and uses of technological tests, one based on earlier work in the sociology of science dealing with the construction of scientific experiments. Sociologists and historians understand both as interpretive processes in which the generalized results do not necessarily reflect the "natural" properties of materials or technologies but rather the assumptions of laboratory workers mediated by external social, political, cultural and economic factors. As such, the results are "always open to challenge."[19] I posit that the reasons research and development has persisted despite the repeated failure to produce fuel cells as cheap and durable as incumbent internal combustion and battery power technologies have to do with the ways that British, American and, more recently, Canadian research communities have

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Computing (1998), David Noble's *Forces of Production* (1986), Bruno Latour's *Aramis, or, The Love of Technology* (1996), David A. Kirsch's *The Electric Vehicle and the Burden of* History (2000), Gijs Mom's *The Electric Vehicle: Technology and Expectations In the Automobile Age* (2004) and Richard H. Schallenberg's *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (1982).

[19] Trevor Pinch, Malcolm Ashmore and Michael Mulkay, "Technology, Testing, Text: Clinical Budgeting in the U.K. National Health Service," in *Shaping Technology/Building Society: Studies in Socio-Technical Change*, eds. Wiebe E. Bijker and John Law (Cambridge, MA: The MIT Press, 1992), 273.

used tests to draft standards of success.[20] These research communities, I argue, have collectively acted as the leading generators of expectations for an affordable and robust commercial fuel cell in the post-Second World War period.

Donald MacKenzie and Trevor Pinch's studies of how people test technology offer several generalizations useful for the case of fuel cells. MacKenzie holds that testing has been an important means by which people come to develop knowledge of artifacts, which in turn helps determine how they are designed and how widely they are adopted in society. As such, testing is a process of shaping rather than revealing facts. MacKenzie observes the tendency of research communities to treat technological knowledge, like scientific, mathematical and medical knowledge, as "hard fact," when the conventions of technology-testing are actually the product of decisions made on the basis of tradition, experience and vested interests, in short, a wide variety of non-technical factors. Justifications for technological choice made on the basis of technical superiority or greater efficiency cannot be considered absolute, given that definitions of superiority and efficiency may vary in different contexts and circumstances.[21]

For a variety of reasons, designers of tests have desired unambiguous results and total control over "potential disturbing factors," producing conditions dissimilar to those technologies will likely encounter in real-world applications and allowing inferences to be drawn between certain artifacts and others in their class.[22] Pinch describes this as a process of making "similarity judgments," a mode of simplification whereby researchers set aside those things that "make for differences" on the basis of a wide range of assumptions. Pinch describes three different kinds of test to which people subject technology, all of which involve making similarity judgments projecting future performance. Prospective testing determines the feasibility of design and can involve scale models, full-scale prototypes and manufactured goods before they are released into the marketplace. Current testing assesses equipment that is already in wide use; and retrospective tests are designed to diagnose the causes of catastrophic failures of in-service technologies.[23] The conventions of reporting "successful" tests often involve omitting all reference to the circumstances in which the test was executed.

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[20] Classic studies of tests and experiments include Steve Woolgar and Bruno Latour's *Laboratory Life* (1976), Edward Constant's *The Origins of the Turbojet Revolution* (1980), Trevor Pinch's *Confronting Nature: the Sociology of Solar Neutrino Detection* (1986), Steven Shapin and Simon Schaffer's *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life* (1986) and Donald MacKenzie's *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (1990).

[21] Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: The MIT Press, 1990), 9-10, 340-381. In his sociological analysis of ballistic missile guidance technology, MacKenzie observes that researchers first developed assumptions of the capabilities of such systems at the laboratory level. Various components of ballistic missiles - the warhead, rocket booster and guidance package - were individually tested in controlled conditions, bolstering further expectations of performance. For a variety of political reasons, complete nuclear-armed intercontinental ballistic missiles have not been tested from their operational silos under realistic conditions in the U.S. MacKenzie thus questions the accuracy missile-builders claim for their weapons.

Though British and American fuel cell research and development communities in the postwar period employed all three types of testing outlined by Pinch, prospective testing has dominated. This is because so few fuel cell systems have gone through the entire cycle of development and been placed into large-scale production. This, in turn, is both the cause and consequence of the material practices of these communities, which have unfolded in a linear manner both as a result of the management techniques of their patrons and the unique nature of fuel cell technology. While government, industry and the financial community have devoted considerable resources researching fuel cells and associated technologies, such support has been intermittent, as evidenced in the two postwar boom-bust cycles. The limited availability of electrochemical expertise and uncertain access to funding has made commercial fuel cell research and development a highly speculative and tenuous enterprise. Securing steady sources of capital was a constant concern of fuel cell workers. This helped foster the psychosocial conditions that validated and reinforced the notion of "technological breakthrough," involving dramatic demonstrations of power output obtained on simple laboratory fuel cells. High power output became the chief criterion of a successful fuel cell and the key driver of expectations.

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[22] MacKenzie, "From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy," in *The Uses of Experiment: Studies in the Natural Sciences*, eds. David Gooding, Trevor Pinch and Simon Schaffer (Cambridge: Cambridge University Press, 1989), 414-415.
[23] Trevor Pinch, "'Testing-One, Two, Three…Testing!'" Toward a Sociology of Testing," *Science, Technology & Human Values* 18, no.1 (winter 1993): 27-31.

This preoccupation with power stemmed from two factors: the respective ways researchers distinguished between and classified fuel cells and storage batteries and the political economy of fuel cell research and development communities. Batteries and fuel cells operate on similar physical principles, combining a chemical fuel and oxidant in an electrochemical reaction that yields electrical current and a chemical waste product. As noted earlier, batteries have their own self-contained chemical reactants. Rechargeable storage cells combine these reactants to produce electricity and waste products, which build up within the battery and reduce its efficiency as it discharges. The cell is then "recharged" with externally produced electricity, which dissociates the wastes back into the original chemical constituents. Such devices are said to be "reversible." They are measured in terms of their capacity to store electricity relative to their volume and supply it for a given period of time. This is typically expressed in terms of watt-hours per litre or "energy density."

In contrast, fuel cells are merely a kind of energy converter with no intrinsic storage capacity at all. Their chemical fuel is instead stored in external tanks; the fuel cell itself has no measurable "energy density." Researchers have consequently developed alternate means of rating the technology: "current density," the amount of current produced in a given area of the chemical reactor as the result of an electrochemical reaction, measured by milliamperes per square centimeter or amperes per square meter, and "power density," the ratio of power available for useful work to weight or volume, measured by watts per kilogram or liter. Importantly, these units of measurement are not expressed in terms of a time relationship, as with conventional storage batteries. Many researchers simply assumed that as long as fuel was supplied to fuel cells, they would continue to operate "invariantly," with no internal chemical deterioration over time, unlike batteries. Indeed, fuel cells have instead struck most chemical and electrochemical engineers as having more in common with the conventional internal combustion engine than the storage cell or battery.[24] They have posited fuel cells as a hybrid of battery and heat engine, combining the best features of both in a sort of electrochemical engine that consumes fuel and produces electricity in a single irreversible electrochemical reaction.[25]

As we have seen, fuel cells are subject to similar sorts of chemical side reactions and deterioration over time that afflict batteries. In order to be practicable, fuel cells also require fuel storage and/or production systems, complex technologies in their own right. However, during the initial stage of postwar fuel cell research and development programs, researchers typically set these sub-systems aside, concentrating instead on improving the power output of the fuel cell energy converter. This occurred for two reasons: fuel cells had to be made powerful before they could be considered practical, but it was also much easier to boost the power of fuel cells than to develop them as fully integrated miniature chemical plants. Consequently, advances in fuel storage and production technologies have historically trailed those in fuel cell energy converters.

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[24] John O'M. Bockris and Z. Nagy, *Electrochemistry for Ecologists* (New York: Plenum Press, 1974), 64-65.

[25] For example, see A.D.S. Tantram, "Fuel Cells: Past, Present and Future," *Energy Policy* (March 1974): 56; John O'M., Bockris and Amulya K.N. Reddy, *Modern Electrochemistry 2B: Electrodics in Chemistry, Engineering, Biology and Environmental Science*, 2nd ed. (New York: Klúwer Academic/Plenum Publishers, 2000), 1811; Ballard Power Systems, Inc., *Annual Report* 1996 (1997), *Annual Report* 1997 (1998), *Annual Report* 1998 (1999), *Annual Report* 1999 (2000), *Annual Report* 2000 (2001), *Annual Report* 2001 (2002), *Annual Report* 2002 (2003).

In this sense, the history of fuel cell research and development provides an interesting contrast with the development of electrical grids as described by Thomas P. Hughes. He coined the term "reverse salient" as an analytical metaphor to account for the expansion of these technological systems, analogizing the process of innovation to a military front. While the front may generally advance, it does so asymmetrically. In certain places, pockets of resistance retard overall progress and are focused on by engineers accordingly. When these areas are mastered, the front may again advance.[26]

In contrast, the reductive focus of fuel cell researchers on "reverse salients" mainly within the fuel cell energy converter has, paradoxically, tended to build expectations and attract a wide variety of sponsors while inhibiting the development of fuel cell systems. The resulting linear linkage between progress and funding typically broke down as researchers made fuel cells larger and more complex. Early experiments generally employed simple laboratory fuel cells using pure hydrogen and oxygen.

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[26] Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, MD: Johns Hopkins University Press, 1983), 14, 80.

These reactants were expensive, but yielded high current densities. Increasing power output became the standard benchmark of progress and the chief political capital of researchers, attracting sponsors and investment. As researchers learned more about fuel cells, they made two important judgments about their nature, with important consequences for the future conduct of research and development. They learned that fuel cells had the same level of efficiency regardless of size, unlike conventional heat engines; researchers came to believe that fuel cells could be used in a wide range of applications ranging from tens of watts to tens of millions of watts. The second judgment was more contentious. Successful demonstrations of fuel cells using hydrogen led researchers to expect similar progress on larger and more powerful fuel cells using cheaper but more chemically complex carbonaceous and hydrocarbon fuels. Together, these judgments gave rise to the notion of the fuel cell as a universal energy converter, capable of employing a wide variety of hydrogenous fuels in a number of applications and working equally well in all. This has facilitated the process of alliance-building that Callon noted in the French context, attracting a wide variety of sponsors including the battery, chemical, oil and auto industries, as well as gas and electric utilities and military organizations.

As researchers developed more complex testing regimes for more sophisticated fuel cells, however, they discovered that such technologies worked well in only certain contexts and applications. Making fuel cells durable and affordable, an expensive and time-consuming process known as “engineering research,” involved a completely different non-linear political economy than early-stage research and development. Engineering research involved long tests of scaled-up fuel cells in realistic operating conditions. Here, success was no longer gauged solely in terms of dramatic increases in power output but by slow incremental improvements in durability and cost-effectiveness. However, larger hydrogen fuel cells behaved quite unlike simpler equipment used in short-term tests, displaying adverse physico-chemical reactions over longer periods of time. The same was true for hydrocarbon fuel cells, except that these had much worse performance and durability than models using hydrogen. Matters became still more complex when fuel cells of all types were integrated with fuel production and/or storage systems and mated with appliances. This imposed stresses on the fuel cell energy converter that varied according to the demand for power, with further unpredictable consequences in terms of interactions between materials. Once the pace of breakthrough power demonstrations slowed as research communities struggled to make fuel cell systems cost-effective and durable, the result was typically a crisis of expectation in which government and industry sponsors reduced or completely withdrew their patronage.

The judgments research and development communities made of the similarities between laboratory and full-sized fuel cells and between hydrogen and hydrocarbon fuel cells were further conditioned by "technopolitics," the "strategic practice of designing or using technology to constitute, embody or enact political goals."[27] These dynamics play out within "technopolitical regimes," groups of people and engineering and industrial practices that "act together to govern technological development."[28] While researchers and their sponsors shared similar assumptions in the actual process of research and development, they nevertheless belonged to disparate cultures with differing institutional priorities, definitions of "research" and "development" and standards of what constituted a successful fuel cell. Expanding on and elucidating Callon's notion of technological simplification, I explore how British, American and Canadian technopolitical regimes tried to make fuel cell technology "work" in different socio-economic and cultural settings. I argue that these regimes successively arbitrated expectations and the conduct of research and development in ways that crucially impinged upon the two major postwar fuel cell booms.

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[27] Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War II* (Cambridge, MA: The MIT Press, 1998), 15.
[28] Ibid.

Outline

I trace the origins of the chain of expectations in post-Second World War fuel cell research and development to Francis Thomas Bacon, the English engineer widely acknowledged in the technical literature as the "father" of the first practical fuel cell. Chapter One explores the making of the "Bacon Cell," a device that played a major role in sparking a wave of interest in the United States in the late 1950s that led to the first postwar fuel cell boom. Unappreciated in Britain, the Bacon cell became an exemplar of fuel cell technology when it was adopted by the National Aeronautics and Space Administration to serve as the power source for the Apollo moon spacecraft. This chapter addresses the development of the Bacon cell and the circumstances that led to its transfer to the U.S., introducing technopolitical relationships that would recur in subsequent fuel cell programs. Later chapters will examine research and development in light of the Bacon cell's symbolic and ideological function as a "success" story.

Chapter Two examines the role of the U.S. Department of Defense's Advanced Research Projects Agency (ARPA) in defining and popularizing notions of the fuel cell as a miracle battery. As a major sponsor of basic research in support of sophisticated military technology, ARPA predicted that the fuel cell's first successful application would be in missiles and spacecraft. The agency's belief that all fuel cell applications were more or less alike had a significant impact in shaping the expectations of interested agencies, particularly the Army. I explore ARPA's role as the manager of "Project Lorraine," a program of basic and applied research on hydrocarbon electro-oxidation that began in 1960. This episode in fuel cell history has hitherto remained largely unexplored, absent even from the technical literature. While American military involvement in fuel cell research has been dated from 1965, the year the Army began its fuel cell technology program,[29] I argue that the efforts of ARPA in the preceding five years played a crucial role in determining the conduct of the Army fuel cell program. ARPA and Army planners created a requirement for a general-purpose fuel cell expected to operate flawlessly in any application in all climatic conditions and on any carbonaceous fuel that happened to be available. What was more, this power source was to be built on a strict timeline and on a relatively small budget. As in the space program, industrial contractors harbored hopes of adapting for commercial use the fuel cells they developed for the government.

Project Lorraine affords crucial insight into the technopolitical relationships that emerged between laboratory workers and researcher sponsors in the United States. As in the British program, a gap emerged between expectations developed in relation to laboratory work and the actual needs of end-users. Because the heavy, chemically complex fuels used by the armed forces were difficult to completely reduce to hydrogen in fuel cells, industrial contractors resorted to other fuels that were more easily oxidized. This allowed them to achieve "successes," gain access to further funding and build expectations for commercial sales. Despite much promotion, the resulting fuel cell systems met neither commercial nor military requirements.

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[29] Appleby and Foulkes, *Fuel Cell Handbook*, 151.

Chapter Three explores ARPA's efforts to justify these research programs as Project Lorraine drew to a close in 1965, along with the Army's efforts to apply the results. The knowledge yielded in the reductive and controlled circumstances of the laboratory left industry and Army engineers ill-prepared to face the challenges of developing full-scale prototype hydrocarbon cells. The Army hoped to use such devices with portable radios and radars. But as it tested fuel cells in these applications, problems arose that had not been anticipated during Project Lorraine. During the very earliest stages of basic and applied research, workers rarely considered how the electrical load demand of the appliance - the "duty cycle"- might affect the entire system. Different appliances had different duty cycles: some drew relatively constant amounts of power while others called for it intermittently. Such irregular use, researchers found, imposed great demands on the control equipment necessary for responding quickly to electrical demand, adding fuel, removing waste and maintaining the chemical equilibrium within the fuel cell reactor required for long life. These interrelated systems were additionally stressed when hydrocarbon fuels were introduced into them. Despite the importance of control sensors, they were typically the last subsystem to be considered by fuel cell workers.

Chapter Four assesses the fuel cell program of the NASA. It reprises the story of the transfer of Bacon cell technology and details its reincarnation as the power source for the Apollo spacecraft. Here, I address the material and ideological legacy of the federal government's sponsorship of fuel cells in the 1960s and early 1970s, one of the many unresolved questions in the modern history of fuel cells. Focusing on NASA's relationship with Pratt & Whitney, the space agency's main fuel cell contractor, I explore how each actor tried to use the aerospace fuel cell program to achieve broader political and economic objectives. For NASA, the fuel cell was attractive in two ways. It was useful both as a power source well-suited to the rigours of space travel and as political capital in the agency's battles with Congress over the relevance of the space program, serving as an example of a Space Race byproduct beneficial to the American economy. Pratt & Whitney acquired a license for the Bacon patents, which it used as the basis for its hydrogen fuel cell for the Apollo spacecraft. But the company also nurtured dreams of developing a commercial hydrocarbon fuel cell. Although Pratt & Whitney has denied that NASA and aerospace fuel cell contracts benefited its commercial program, I demonstrate that the experience, personnel and equipment accumulated as a result of this relationship was crucial in allowing the company to develop the world's first industrial fuel cell manufacturing capability.

All the tendencies in fuel cell research and development that had developed over some three decades following the end of the Second World War were re-enacted in the socio-economic and political circumstances of the 1990s, the subject of Chapter Five. This time, expectations coalesced around the fuel cell automobile, long the lodestone in the dreams of fuel cell enthusiasts. In an era when clean energy had become an indispensable political consideration in the marketing of automotive technology, the idea of a fuel cell electric automobile able to combine environmental sustainability with the comfort and performance of gasoline automobiles had considerable popular appeal. In such an automobile, the dream of the fuel cell as a universal energy converter was reborn once more, engaging the massive resources of the automobile industry and, subsequently, the federal government's energy research and development apparatus.

The historical lessons of the shortfall between boundless expectation and the social and physical limits of fuel cell technology seemed lost on the latest generation of researchers. As technologists struggled to miniaturize the hydrocarbon fuel cell for the vehicle application, the automobile industry and then the federal government looked back to the hydrogen fuel cell. By the turn of the millennium, the idea of a fuel cell-based hydrogen economy began to gain currency in American popular science culture. In the words of one visionary pundit, such an energy order would "fundamentally reconfigure human relationships," displacing centralized hydrocarbon-based energy production systems and bringing the energy and environmental crises to an end.[30]

Paradoxically, as technical problems in fuel cell technology programs mounted, the expectations of industrial and political elites increased. In the early 2000s, they claimed that the fuel cell automobile was the ultimate solution for sustainable transport, facilitating the reduction of U.S. petroleum consumption, greenhouse gas emissions and dependency on foreign oil. In this sense, the fuel cell-based hydrogen economy has been framed as a technological energy utopia, a characteristically American cultural *leitmotif*.[31]

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[30] Jeremy Rifkin, *The Hydrogen Economy: The Creation of the World-Wide Energy Web and the Redistribution of Power on Earth* (New York: Jeremy P. Tarcher/Penguin, 2002), 9.

At first sight, the eagerness of the automobile and oil industries to pursue the fuel cell electric automobile appeared to run contrary to the widespread belief that new technologies represent a threat to established interests, causing a reaction that often blocks the spread of new devices.[32] As this chapter will demonstrate, political and industrial elites were prepared neither to launch the new industrial revolution that the commercial fuel cell electric automobile required nor moderate their expectations to accord with the physical limitations of fuel cell technology and their own socio-economic and cultural credos. Through their insistence that this technology will pave the way for a brave new world, these elites have created the ultimate fuel cell technopolitical regime, where the perpetual promise of a miracle battery and a radical break with the unsustainable policies of the past is used to forestall radical social and technological change in the hydrocarbon-based transportation system. As such, this is the latest episode in what historian of technology Langdon Winner has referred to as the long-standing tradition in the American polity of using technology as a substitute for politics.[33]

Sources

The primary sources used in this dissertation are drawn from the Churchill College Archives Centre in Cambridge, England; the National Archives and Records

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[31] George Basalla, "Some Persistent Energy Myths," in *Energy and Transport: Historical Perspectives on Policy Issues*, eds. George H. Daniels and Mark H. Rose (Beverly Hills, CA: Sage Publications, 1982), 27; Howard P. Segal, *Technological Utopianism in American Culture* (Chicago: University of Chicago Press, 1985), 1-22.

[32] Nathan Rosenberg, "On Technological Expectations," in *Inside the Black Box: Technology and Economics* (New York: Oxford University Press, 1982), 104-119.

[33] Langdon Winner, *Autonomous Technology: Technics Out-of-Control as a Theme in Political Thought* (Cambridge, MA: MIT Press, 1977), 237.

Administration (NARA) depository in College Park, Maryland; the National Aeronautics and Space Administration Headquarters library and archive, the Smithsonian Institution's general archive and its National Air and Space Museum archive, all in Washington, D.C.; the Army Communications and Electronics Command Historical Research Collection at Fort Monmouth, New Jersey; and the Neumann Library at the University of Houston in Clear Lake, Texas. These materials include the personal correspondence of researchers and administrators, interdepartmental memos, minutes of meetings, interviews and internal reports, none of which has been previously exploited in a scholarly analysis on this topic.

For historians of technology, the technopolitics of industrial research and development, the daily record of research, failed experiments, personal disputes, and interdepartmental conflicts oftentimes represent a forbidden world made inaccessible by private property restrictions. The Bacon papers at the Churchill College Archives Centre were extremely useful in shedding light into this hidden realm and were the single most important resource for this project. They comprise a rich concentration of material collected over a period of almost 70 years between the 1920s and 1990s. An inveterate letter-writer, Bacon was well-connected in both the scientific and engineering worlds. He was on intimate terms with many of the leading figures involved in the electrochemical and fuel cell fields in academe, industry and government in Britain, Europe and the United States.[34] Moreover, the collection contains numerous items from Energy Conversion Limited, a British public-private corporation that had access to some Pratt & Whitney research through its licensing relationship via the Bacon patents.

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[34] At one time or another, Bacon was on friendly terms or corresponded with Ernst Cohn (U.S. Army and NASA), D.L. Douglas (General Electric), Galen R. Frysinger (U.S. Army Electronics Command), D.P. Gregory (Energy Conversion Limited, Institute of Gas Technology), Eduard Justi (Technical University, Braunschweig), Karl V. Kordesch (Union Carbide), H.A. Liebhafsky (General Electric), Anthony Moos (Leesona-Moos), John O'M. Bockris (University of Pennsylvania, University of Adelaide), Harry Oswin (Leesona-Moos), William Podolny (Pratt & Whitney division of United

The Bacon papers proved extremely versatile. I used them not only to explore the relationship between laboratory researchers and private and government sponsors of fuel cell technology in both the United States and Britain, but also to map the transfer of the Bacon cell from the various sponsoring institutions in these two countries and to gauge the reaction of researchers all over the world as that occurred. In this way, I was able to trace both the material and ideological influence of the technology from the modestly equipped laboratories at King's College London and Cambridge University where Bacon began his research to the lavish test facilities of General Electric, Pratt & Whitney and NASA in New York, Connecticut and New Mexico respectively.

The records of the U.S. federal government have also provided insight into the hidden realm of the industrial laboratory. The government's role as both the chief administrator of industry's fuel cell programs and their main customer in the 1960s and 1970s placed the bureaucratic paper trail of the corporate research and development laboratory in the public realm. The result was a considerable body of material, including requests for proposals, proposals, contracts and progress reports concentrated at the National Archives and Records Administration and the NASA Headquarters archive and library. The National Archive's collection of papers pertaining to ARPA's Project Lorraine is an especially valuable resource that lays

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Aircraft/United Technologies Corporation), K.R. Williams (Shell) and Ernest Yeager (Western Reserve University), to name only the most important.

bare the decision-making processes of a major federal military sponsor of basic research. Besides a wealth of memos and correspondence, the collection includes a number of valuable laboratory reports from private contractors. The NASA materials are also important and include extensive test results and progress reports from General Electric and Pratt & Whitney's fuel cell programs, as well as extensive records of the space agency's in-house research and development effort.

1 - Laboratory Demonstrations and Great Expectations

For Francis Thomas Bacon, success came relatively late in life. When it did, it came in a flush. Over a period of eight years beginning in 1965, he was showered with the kinds of honours for achievement in science and technology typically reserved for only an elite few. At age 61, he was awarded the S.G. Brown Award and Medal by the Royal Society of Britain. In 1969, Bacon was a recipient of the British Silver Medal of the Royal Aeronautical Society. His accomplishments were hailed in personal meetings with the president of the United States, the prime minister of Great Britain and the Apollo 11 moon astronauts. In 1972, Bacon received the Churchill Gold Medal Award of the Society of Engineers. Finally, in 1973, at 69, he was elected Fellow of the Royal Society, joining the select ranks in Britain's pantheon of illustrious personages of science and technology.

This rapid rise might well have been expected from someone with a pedigree as distinguished as Bacon's. He claimed direct descent from Sir Nicholas Bacon, the father of Sir Francis Bacon, the great English philosopher of the seventeenth century.[1] Bacon is widely acknowledged in the technical literature as the inventor of the first practical fuel cell, a design that achieved fame as the power source for American spacecraft. It also played an important role in shaping perceptions of the potential of fuel cell technology in the 1950s and 1960s. Yet virtually nothing is known of how Bacon, a self-employed mechanical engineer with no formal electrochemical training, brought his device from the laboratory bench to the attention of the broader engineering and scientific community.

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[1] K.R. Williams, "Francis Thomas Bacon, 21 December, 1904-24 May 1992," *Biographical Memoirs of Fellows of the Royal Society* 39 (February 1994): 3, 11-12. It is also possible that Bacon was related to the family of Roger Bacon, the thirteenth-century natural philosopher.

Bacon's experiences as a fuel cell developer were bittersweet. Between 1946 and 1959, he won support from a succession of British sponsors of research and development. Yet during this time, he toiled fruitlessly to convince potential customers of the utility of his device. This chapter explores the development of the Bacon cell as it moved through these social, cultural and technical realms. I expand on Callon's understanding of the factors driving fuel cell development, noting that the flexibility of the fuel cell concept gave it broad appeal to a wide variety of actors with disparate interests. In Britain in the 1950s, the Bacon cell was a powerful symbol of national technological prowess. For some, it was merely a superior kind of storage battery; for others, it was the vanguard of an electrochemical revolution that would supplant the internal combustion engine.

I root these social dynamics in the relationship between Bacon and his chief sponsors, the Electrical Research Association (ERA) and the National Research Development Corporation (NRDC). In particular, I note how perceptions of the utility of fuel cell testing varied greatly depending on how the relevant interest groups understood the process of "research and development." As the ERA and NRDC supported Bacon's work in the 1940s and 1950s, boundaries between "research" and "development," between "basic" and "applied" research, tended to blur. While the ERA funded applied research in support of existing technologies, its directors never fully understood the end served by its support of the Bacon cell: was the goal commercial development or was it merely to investigate the Bacon cell's suitability for development?

For Bacon, the categories of "basic" and "applied" research were not mutually exclusive but part of a singular process. Despite his sponsors' uncertainty over the utility of the technology, Bacon and his research team interpreted their support as the first stage in developing the device for commercial purposes. In turn, Bacon's ability to rapidly improve the fuel cell's power output persuaded funding agencies that the technology was more than simply a curiosity. Despite the fact that few could find a clear use for the "Bacon cell," steady improvements made during the technology's prolonged gestation nurtured expectations that it would one day emerge with "miracle" properties. This, in turn, helped stoke interest in fuel cell technology in the United States.

The historiography of fuel cell research and development is almost entirely an "internalist" one. Because most of the leading technical accounts have been written by leading fuel cell researchers, such authors tend to focus heavily on laboratory developments and finished pieces of technology.[2] While these researchers do often refer to "external" conditions - the general social, political and economic factors that helped inform research and development programs - they rarely refer to the techno-political relationships between laboratory workers and the sponsors of research. Perhaps more surprisingly, these sources have rarely attempted to theorize the broader sweep of fuel cell history and to explore why high expectations have been so consistently been invoked, and just as consistently disappointed. In setting the groundwork to address these lacunae, an exploration of the work of Francis Thomas Bacon is crucial, for it will allow us to address the general and the unique, continuity and change, in the historical practice of fuel cell research and development.

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[2] This applies to Bacon's own recollection of his work in an address delivered to the Vittorio de Nora-Diamond Shamrock society in Seattle, Washington in May 1978. Reproduced in the January 1979 issue of the *Journal of the Electrochemical Society*, this address is the most detailed account of Bacon's work. The technical treatises with the most extensive treatments of the history of fuel cells include H.A. Liebhafsky and E.J. Cairns' *Fuel Cells and Fuel Batteries* (1968), Bernard J. Crowe's *Fuel Cells: A Survey* (1973), A.J. Appleby and F.R. Foulkes' *Fuel Cell Handbook* (1989), Karl Kordesch and Günter Simader's *Fuel Cells and their Applications* (1996), and Vielstich, Lamm and Gasteiger's *Handbook of Fuel Cells: Fundamentals, Technology and Applications* (2003).

What's in a Name? From "Reversible Cell" to "Fuel Cell"

In examining the Bacon cell in its various stages of development, a gulf becomes apparent between the perceptions of the laboratory teams and their sponsors regarding the goals of work, the conduct of research and the application to which the finished product would be put - tendencies that characterize current fuel cell research and development. Historical essays written by Bacon and his contemporary Karl Kordesch raise these general issues and provide a starting point in introducing the socio-economic and technopolitical context within which pioneering fuel cell researchers worked. While there were many different fuel cell designs in the 1950s, says Kordesch, all were realized by addressing seven technical points. Of these, the last two are the most contentious: "recognizing the fuel cell as a 'system' (i.e.: as a primary cell with continually supplied chemicals)" and "learning that success depended on the functioning of the auxiliary components as much as on the electrochemical reactions."[3]

As I shall demonstrate, post-war fuel cell researchers have in fact generally *not* recognized the fuel cell as a system, paying much more attention to the fuel cell reactor itself and much less to fuel production and storage technologies. The discrepancy has stemmed largely from problematic definitions of what constitutes a fuel cell, which in turn stems from confusion in the literature regarding the technology's etymology. This has important implications for conceptions of a fuel cell as a system and for how people have gone about researching and developing it.

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[3] The others are porous electrode structures, inert conductive substructures, catalysts, pressure or high temperature for a high reaction rate, wetproofing or gas pressure balance for stability, and gases (later also liquids) as fuel; Karl Kordesch, "25 Years of Fuel Cell Development (1951-1976)," *Journal of the Electrochemical Society* 125, no. 3 (March 1978): 78C.

The electrochemical energy conversion technology now known as the fuel cell has not always been referred to as such. As previously mentioned, what is now known as the fuel cell effect was originally discovered in the late 1830s and early 1840s by European scientists who reversed the electrolysis phenomenon. William Grove combined hydrogen and oxygen in sulfuric acid cells to provide electricity for electrolysis, decomposing water by the means of its composition, as he put it. He referred to this device as a "gaseous voltaic battery."[4] The term "fuel cell" was first applied to such an electrochemical device by Ludwig Mond and Charles Langer in the 1880s. This referred to the *source* of the hydrogen that was fed into the cell, which was derived from coal.[5] In the late nineteenth and early twentieth centuries, researchers like W.W. Jacques and Emil Baur focused on attempting to effect the direct electrochemical conversion of coal in high-temperature devices. By the time Bacon began his first investigations in the early 1930s, the term "fuel cell" had come to be associated in the chemical community with a device that used either carbonaceous fuel or "dirty" hydrogen derived from carbonaceous substances, not pure hydrogen.

The early carbonaceous fuel electrochemical energy converters were primary devices. Like disposable galvanic batteries, they consumed their chemical fuel in a single *irreversible* reaction. That is, the fuel was electro-oxidized to produce electricity and the waste ash was discarded. These fuel cells were completely impractical because carbonaceous fuels used directly in the reactor chamber quickly contaminated catalysts and electrolytes, bringing about the destruction of the cell. Conversely, Bacon conceived the "fuel cell" as a *reversible* device to store electricity. As an employee for the British engineering firm C.A. Parsons in the early 1930s, Bacon had become intrigued with the possibility of reversing water electrolysis. His inspiration was an article in the professional journal *Engineering* outlining a German idea for using off-peak electricity to produce hydrogen from water, which would fuel an internal combustion engine. Bacon wondered if it might be even more efficient to run the hydrogen through a fuel cell. The device would function like a secondary or storage battery, except it would use hydrogen and oxygen to produce electricity. It could then be "recharged" by subjecting the waste water to electrolysis using electricity produced from an outside energy source.[6]

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[4] William Robert Grove, "On A Gaseous Voltaic Battery," *Philosophical Magazine and Journal of Science* 21, S.3 (December 1842), 417.

[5] H.A. Liebhafsky and E.J. Cairns, *Fuel Cells and Fuel Batteries: A Guide to their Research and Development* (New York: John Wiley & Sons, 1968), 23.

Between 1932 and 1940, Bacon worked on his device on his own time, basing it on electrolyzer technology. After experimentation, he decided that the great weakness of a low-temperature device using an acidic electrolyte was that it required expensive platinum to catalyze the reaction and created a corrosive environment that broke down cell materials. On the other hand, an alkaline electrolyte allowed the use of cheap nickel as an electrocatalyst if used at over 200°C. At this temperature, high pressure was necessary to prevent the electrolyte from boiling; Bacon found that increasing the pressure even further boosted performance.[7] The main shortcoming of using alkaline electrolyte in an electrochemical cell was that it was susceptible to contamination from carbon. Because Bacon planned to use pure hydrogen and oxygen, he did not see this as a handicap.

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[6] Francis Thomas Bacon, "The Fuel Cell: Some Thought and Reflections," *Journal of the Electrochemical Society* 126, no. 1 (January 1979): 7C.

Bacon understood his fuel cell/electrolyzer, or "reversible cell," as he called it, as a storage device. However, it did not have any intrinsic storage capacity. It was simply an electrochemical energy converter; its fuel was stored *externally*. This had important implications for the construction of a fuel cell system. While fuel storage was not an issue for a carbonaceous fuel cell, which could use existing receptacles for liquid or solid fuels, the storage cell's dependence on hydrogen posed technical problems, for it was a costly fuel with properties that made it difficult to store in large quantities.

In short, Bacon's "reversible cell" depended on advanced and as-yet undeveloped hydrogen storage technologies in order to be commercially feasible. In his early research, he did not seriously consider this, likely because he had begun without any clear applications in mind. As Bacon noted in his historical review, he believed he first needed to perfect the energy conversion unit before possible commercial roles would become apparent.[8] As such, he devoted his energies to the specific technical problems relating to the "reversible cell," of which there were many.

The first sponsors of his technology would share Bacon's reductive understanding of the "reversible cell" as a technological system. This had important implications for the conduct of the research and development of the Bacon cell, as it came to be known. As Bacon improved the device's power output in the late 1930s and early 1940s and began to attract attention in the British engineering community, his first sponsor, the Electrical Research Association (ERA), showed no more inclination than he to consider hydrogen storage technology. Its managers, too, emphasized the energy conversion unit, but were less convinced of its utility as a reversible storage device. The result was that the ERA's support became contingent on the gradual reconceptualization of the Bacon "reversible cell" as a "fuel cell." With this came the understanding that the device would no longer function reversibly but irreversibly. In turn, this implied that the technology would operate on hydrocarbon fuels, a function it was ill-suited to fulfill.

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[7] Bacon, "Research into the Properties of the Hydrogen-Oxygen Fuel Cell," *British Electrical and Allied Manufacturers Association Journal* 61, no. 6 (summer 1954): 6-8; A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), 4, 387.

[8] Bacon, "The Fuel Cell: Some Thoughts and Reflections," 7C.

British Industrial Research and the Bacon Cell

The development of the Bacon cell must be read in light of the key debate in the historiography of British business and innovation in the twentieth century. Since the 1950s, positions have polarized on the relationship between research, development, technology and economic prosperity. One school, in existence since the late 1950s and more recently championed by scholars including Correlli Barnett, Martin Wiener and David C. Mowery, has argued that Britain's economy has slowly but steadily declined throughout the twentieth century owing to the failure of government and industry to develop an effective research and development policy. The result, to quote Barnett, was a social malaise known as the "British Disease," characterized by moribund industry, a backward educational system, an obdurate, ill-trained workforce and a pervasive "anti-technical bias" that stultified technological innovation.[9] Mowery blamed poor organization and planning by industry, but reserved his strongest criticism for British governments. Not only had they inadequately funded technical training programs but also had helped foster an inefficient dual system of industrial research and development. During and after the First World War, the state had intervened to create cooperative research organizations - the so-called research associations - as a means of compensating for the lack of in-house research capabilities within smaller corporations.[10] Consequently, claimed Mowery, parallel systems of industrial research had evolved in the British economy. On the one hand, the state-backed collective research agencies served smaller companies that often lacked the resources and technical means to apply this research; in contrast, the largest and richest corporations had their own in-house laboratories.[11] To the "declinist" mind, these cooperative organizations had, at best, little positive effect on British industrial productivity. At worst, they inhibited technological innovation.

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[9] Correlli Barnett, *The Lost Victory: British Dreams, British Reality 1945-1950* (London: Pan Macmillan 1995), xiii.

[10] The origins of the research associations lay in the First World War. The Allied blockade of Germany revealed Britain's dependence on products of scientific industry supplied by its erstwhile trading partner and its own relatively underdeveloped industrial research capabilities. The British government intervened tentatively, encouraging industry to voluntarily form its own cooperative research organizations. It also established the Department of Scientific and Industrial Research (DSIR), a funding agency supporting academic scientific research and education as well as industrial research. These voluntary self-regulating research associations were supposed to be affiliated with or even independent of existing corporations and were eligible for state funding. They were to be coordinated and supervised by the DSIR and any discoveries belonged to the association. Government assistance was intended to be temporary until a research infrastructure was set up, but the research associations continued to be supported by state funds through the Second World War and into the post-war period. Of some 31 original research associations established after the war, the ERA grew to become among the largest and most important, comparable with some of the in-house laboratories of the major industrial firms; see Ian Varcoe, "Co-operative Research Associations in British Industry, 1918-34," *Minerva: Review of Science, Learning and Policy* XIX, no. 3 (autumn 1981): 434-440, 458; David Edgerton, *Science, Technology and the British Industrial 'Decline,' 1870-1970* (Cambridge: Cambridge University Press, 1996), 42-43.

[11] David C. Mowery, "Industrial Research, 1900-1950," *The Decline of the British Economy*, eds. Bernard Elbaum, William Lazonick (Oxford: Clarendon Press, 1986), 190, 206-207.

Since the late 1980s, an anti-declinist view has arisen, championed most recently by the Imperial College historian David Edgerton. It charges the "declinist" school with grossly underestimating investments in British research and development through the first two-thirds of the twentieth century.[12] In 1994, Edgerton observed that declinist scholars considered only state investments in civil research and development, paying undue attention to the cooperative research associations, which accounted for only a small proportion of total spending on research and development. Much more significant, argued Edgerton, were investments in research by the private sector and by the state in the defense sector. When these are considered, British postwar research and development expenditures outstripped all other Western industrialized countries in relative and absolute terms, save the United States.[13]

The fact that the Bacon cell's first sponsor, the ERA, was one of these poorly funded, ostensibly non-innovative cooperative research organizations, presents a paradox. At first glance, the history of the development of Bacon cell seem to bear out the declinist school's thesis that "Britain was good at inventing but bad at developing."[14] Yet the idea that the research associations and the state did not stimulate innovation in *general* is not supported in this case either. As a result of the support of the ERA and subsequently the NRDC, both channels for state funding, the Bacon cell became the world's first practical fuel cell. Though no commercial applications were found for this technology in Britain, its sale to aerospace giant Pratt & Whitney would play a major role in the development of commercial fuel cell technology in the United States. Possession of what was then the world's most powerful fuel cell design enabled Pratt & Whitney to become the chief supplier of fuel cells for NASA, which used them in American spacecraft including the space shuttle. As I shall argue in Chapter Four, Pratt & Whitney/United Technologies Corporation's monopoly of the aerospace market by virtue of the Bacon cell in turn provided the capital and experience that allowed the company to develop a phosphoric acid fuel cell design that was eventually brought to market in the early 1990s.

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[12] See D.E.H. Edgerton, "Science and Technology In British Business History," *Business History* 29, no. 4 (1987): 84-103; D.E.H. Edgerton and S.M. Horrocks, "British Industrial Research and Development Before 1945," *Economic History Review* 47, no. 2 (1994): 213-238; David Edgerton, *Science, Technology and the British Industrial 'Decline,' 1870-1970* (Cambridge: Cambridge University Press, 1996), David Edgerton, *Warfare State: Britain, 1920-1970* (Cambridge: Cambridge University Press, 2006).

[13] D.E.H. Edgerton, "British Industrial R&D, 1900-1970," *The Journal of European Economic History* 23, no. 1 (Spring 1994): 50-53. Edgerton claims that economists and historians have focused on state civilian research and development for practical and cultural reasons. Much more information was available on it compared to private and military research and development. Also a factor was the perennial complaint of influential interest groups, including scientists and engineers, that private industry underinvested in research and development. Moreover, says Edgerton, military research and development has long been ignored by liberal scholars on the assumption that it was a corruption of science, which they saw as an "essentially" civil, progressive force.

[14] See D.E.H. Edgerton, "Science and Technology In British Business History," *Business History* 29, no. 4 (1987): 84.

The key question, insofar as the history of the Bacon cell is concerned, is *why* British sponsors of research and development were good at inventing but bad at developing. In order to understand this, we must understand British industrial research and development policy after the Second World War. On this issue, Sally M. Horrocks makes a number of important points. With the national economy in tatters after nearly six years of war and with the memory of the successful science-based wartime weapons programs fresh in the minds of planners, government leaders exhorted the business community to turn the powers of research to the rejuvenation of British industry. This would best be accomplished, they believed, by bolstering the defense sector and reconstructing the British industrial base, particularly exports. The government urged industry to devote resources to the latter and it responded, raising research expenditures and expanding the science and engineering workforce by 50 per cent between 1945 and 1951. But the post-war Labour government of Clement Atlee was not laissez-faire. It "picked the winners" and "defined what being a winner meant," channeling research resources to those sectors it believed met its goals.[15] The Bacon cell was an anomaly on all counts. Administrators of industrial research could see no obvious application of it in Britain's recovering post-war economy. Ignored by mainstream industry, the technology instead found a home by default in the parallel state-backed industrial research and development complex.

This was likely the consequence of a pervasive "ideology of progress" within government and industry circle, which associated research with national power and generated intense political pressure to innovate in the post-war period. By the war's end, note Edgerton and Horrocks, "propaganda for industrial research" had reached a high pitch.[16] In peacetime, bureaucrats and industrial researchers basked in the afterglow of the successes of wartime science-based engineering and tried to exploit the image of science as a force of progress, often for their own parochial political objectives. During the 1940s, some of the largest British industrial firms with important in-house research programs including Imperial Chemical Industries, Courtaulds and Associated Electrical Industries also developed their own fundamental research laboratories. These hosted speculative scientific work linked to clear commercial objectives, but sometimes such research was also used as a bargaining chip among competing firms and then later abandoned.[17] Horrocks notes that British industry's promotion of research immediately after the war was at least partly calculated to convince the government of the private sector's commitment to the reconstruction drive and forestall possible nationalization.[18]

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[15] Sally M. Horrocks, "Enthusiasm Constrained? British Industrial R&D and the Transition from War to Peace, 1942-1951," *Business History* 41, no. 3 (July 1999), 48, 58.
[16] D.E.H. Edgerton and S.M. Horrocks, "British Industrial Research and Development Before 1945," *Economic History Review* 47, no. 2 (1994): 216.

It was in this context that the ERA decided to support Bacon in 1946. As previously noted, the move represented a break both with the conservative traditions of cooperative industrial research and the trend towards practically-oriented research to serve immediate defence and industrial requirements. In drafting programs of research, the cooperative associations had to consider the needs of all their constituent industries. Because members did not necessarily share similar economic and technological interests, research was determined consensually. Where the ERA was concerned, the range of latitude in planning was further circumscribed by the fact that important industrial producers of electrical equipment such as AEI had their own in-house "basic" and "applied" capabilities. Work in the cooperative research groups thus tended to be limited to the testing and evaluation of existing techniques and technologies rather than projects of "startling novelty."[19] The ERA was primarily concerned with improving the efficiency and reliability of electrical transmission and distribution equipment including switchers, cables, transformers, insulating materials and towers.[20] However, research associations sometimes supported exploratory and investigative research that individual firms were unwilling to engage in themselves.

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[17] D.E.H. Edgerton, "Science and Technology in British Business History," *Business History* 29, no.4 (1987): 89-91.

[18] Horrocks, "Enthusiasm Constrained? British Industrial R&D and the Transition to War and Peace, 1942-1951," 46-48.

[19] Varcoe, "Co-operative Research Associations in British Industry, 1918-34," 462-463.

[20] C.W. Marshall, "ERA and the Electricity Supply Industry," *Cooperative Electrical Research: The Journal of The British Electrical & Allied Industries Research Association* 1 (July 1956): 7-9.

The ERA first decided to support Bacon largely because the "reversible cell" was an unknown quantity. At the height of the postwar reconstruction drive, ERA officials believed the technology, hitherto ignored in other quarters of industry, might be a "diamond in the rough" with revolutionary potential as a practical power source. The association's initial goal was to determine whether Bacon's device lay in its "field of work."[21] The technology was an "a priori case," as the ERA's director Stanley Whitehead put it.[22] While the technical and economic implications of the Bacon cell were then unclear to association officials, they initially supported research on the possibility that it might lead to a lighter and more efficient replacement for the lead acid storage battery.

Although the ERA supported Bacon for nine years, the question of whether the Bacon cell was a legitimate subject of research remained a subject of controversy within Subcommittee F, the body responsible for overseeing electrochemical matters. That prolonged research failed to dispel this uncertainty stemmed from the inability of the administrators of this conservative, profit-minded institution to define the role of science-based "research" and its relationship to "development" in relation to a technology of which practically nothing was known. While British and American fuel cell research and development programs had varied origins and objectives, they shared linear assumptions of technological progress, drawing from lessons learned in the science-based weapons programs during the Second World War. Progress in virtually all postwar fuel cell programs would be measured by incremental improvements in power output and expectations that simple hydrogen-fuelled laboratory devices could be incrementally enlarged and easily converted for operation on carbonaceous and hydrocarbon fuels.

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[21] Unconfirmed Minutes of the Second Meeting, Section Z, Sub-Committee F, Electrical Research Association, 28 November 1947, Papers and Correspondence of Francis Thomas Bacon, Reference Code NCUACS 68.6.97, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.127, 4, Churchill College Archives Centre, University of Cambridge, Cambridge, England (hereafter cited as Bacon TS).
[22] Ibid., 4-5.

As Bacon and subsequent workers would discover, however, fuel cell research and development was a non-linear process. The fuel cell pioneer Karl Kordesch has noted that although electrochemical theory began to expand greatly after the Second World War, it remained underdeveloped in the 1940s and 1950s. Fuel cells were then designed primarily empirically and researchers gradually enlarged the body of theory through constant experimentation.[23] One of the signal features of the history of fuel cells is that while "applied research" has informed their "development," the "development" phase can and routinely has become a renewed search for "physical principles."

As early exploratory work began in 1946, the members of the ERA subcommittee and the research team interpreted the purpose of experiment quite differently, illustrating the ambiguity of the concepts of "basic," "applied" and "engineering" research and the problems attending the use of the terms "research" and "development" where fuel cells were concerned. Some committee members believed that early test results showed the Bacon cell to be impractical and held that only those projects of immediate commercial value should receive further support. Others were not so sure it had no commercial potential and were prepared to risk funds on a longer-term investigation. It was always possible, they argued, that it would be found that the technology was worthy of further support. These administrators defined such exploratory work as "basic" or "fundamental" research. In this sense, then, the very lack of theoretical knowledge on fuel cells was an important justification for the prolongation of extensive experimentation on them.

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[23] Kordesch, "25 Years of Fuel Cell Development (1951-1976)," 78C-79C.

On the other hand, Bacon and his associates interpreted the limited initial support extended by the ERA as an *endorsement* of the technology. Bacon himself had a strongly empirical understanding of "research" and "development," professing more interest in the "technology" of fuel cells than their "underlying scientific principles."[24] As such, while his research team also sometimes defined research as "fundamental," it expected to *apply* the knowledge of physical principles gleaned from early prospective tests of primitive laboratory technology in more sophisticated and powerful designs. However, Bacon's early work on the reversible cell was not guided with a specific application of the power source itself in mind, as we will see shortly.

The "exploratory" faction within the ERA won out. But as the association prepared to extend the program in late 1947, it made clear it would support the Bacon cell not as a "reversible cell" in the storage role but as a "fuel cell." This meant that the electrolyzer had to be abandoned; hydrogen would instead be supplied from gas bottles. In his historical synopsis, Bacon casually refers to this "abolition" in a single line without elaborating. In fact, this decision radically changed the nature of the technology and the thrust of Bacon's research.[25]

Prior to the war, Bacon's work on the fuel cell/electrolyzer was supported by his chief mentor, A.J. Allmand, a professor of chemistry at King's College London. With assistance from the physical chemist and Imperial College lecturer H.J.T. Ellingham, Allmand had authored the classic *Principles of Applied Electrochemistry* in 1924, a work that had a major influence on Bacon. Impressed by his protégé's early efforts in 1940 while under the sponsorship of the consulting engineer firm Merz and McClellan, Allmand provided space in his laboratory and supervised the project.[26] Work proceeded until 1941 and did not resume until 1946. Then it was re-established under the ERA's sponsorship at the Department of Colloid Science at the University of Cambridge under the leadership of the physical chemist Eric Rideal.[27]

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[24] F.T. Bacon and T.M. Fry, "Review Lecture: The Development and Practical Application of Fuel Cells," *Proceedings of the Royal Society of London: Series A, Mathematical and Physical Sciences* 334, no. 1599 (25 September 1973): 428, 446.

[25] Bacon, "The Fuel Cell: Some Thoughts and Reflections," 8C.

In the fall of 1947, Allmand wrote a memorandum to Subcommittee F recommending continuing support for the project focusing only on the energy conversion unit. To Allmand, Bacon's device had more promise as a "fuel cell" rather than a storage device. Implicit in this definition was the assumption that the device would use not hydrogen but a more conventional fuel in the manner of an internal combustion engine, only much more efficiently.[28] The problem with this was that the Bacon cell's alkaline electrolyte solidified or "carbonated" when exposed to carbon, restricting the device to pure hydrogen and oxygen. In any event, developing the Bacon reversible cell as a fuel cell greatly complicated the matter of how fuel would be supplied and stored, for eliminating the electrolyzer "externalized" the fuel supply.

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[26] Williams, "Francis Thomas Bacon, 21 December, 1904-24 May 1992," 6.

[27] Bacon, "Research into the Properties of the Hydrogen-Oxygen Fuel Cell," 8.

[28] Memorandum from A.J. Allmand, 19 November 1947, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.127, 1. It is noteworthy that the two men whose work had so inspired Bacon disagreed with his vision of electrochemical power. Allmand and Ellingham had long understood the attractiveness of the fuel cell in the possibility that it could be made to use carbonaceous fuels, not hydrogen. Should this be achieved, they had written, the result would be a new industrial revolution comparable to the introduction of the steam engine; A.J. Allmand and H.J.T. Ellingham, *The Principles of Applied Electrochemistry* (London: Edward Arnold & Co., 1924), 217-218.

Consequently, commercializing the Bacon fuel cell would depend not only on developing hydrogen storage technology, the main reverse salient of the reversible cell, but now also hydrogen production technology.

The contradiction between the attractions of the Bacon cell's high current density and the economic liabilities attending its reliance on hydrogen would shape the terms of debate within Subcommittee F over the next nine years. As Bacon rapidly improved the power output of his device, the question of its commercial potential remained stubbornly inconclusive owing to uncertainty over the fuel it would ultimately use. Hydrogen was widely viewed in industry as too expensive and difficult to handle, but there were hopes the Bacon cell might one day be adapted to accept cheaper hydrocarbon-based fuels. As the ERA's own ideological commitment to exploratory fundamental research diminished over this period, this assumption, as well as Bacon's ability to yield ever-higher current densities from improved designs, maintained the project's momentum, attracting attention and new industry sponsors in both Britain and the United States.

Gathering for their second meeting a little more than a week after receiving Allmand's memorandum, the members of Subcommittee F were loath to abandon the Bacon cell, yet reluctant to directly address the fuel problem. Instead, the subcommittee invoked new justifications that turned the issue away from the question of fuel and towards the numerous technical problems plaguing the fuel cell unit itself. The group confirmed Allmand's observations, concurring that the Bacon cell in the storage application offered no economic advantages over existing storage battery technology. Bacon also agreed, stating that it "would be best" to abandon the accumulator and "limit the application to a fuel cell."[29] The ERA would not support work on hydrogen production and storage technologies.

But without these systems, the Bacon fuel cell could not function in any commercial role outside the laboratory, begging the question of the economic rationale of the entire effort. The issue was raised by Rideal. Was the point of the effort, he asked, to seek a "technical" or "industrial" solution to the problem? Was it to show that an industrial solution was *not* feasible? Here, Rideal was suggesting that the ERA was verging on areas outside the limited set of research objectives it had delimited. Whitehead, the ERA director, immediately elucidated the point, stating that the association felt that studies should be pursued in fields where knowledge was deficient. With the case at hand, the goal had not been to produce something "economically feasible" but to determine whether or not the fuel cell as an electrochemical technology was within the ERA's field of expertise. If so, the association then wanted to "show that it did work."[30]

This was a major revision of the ERA's original objective, which had been to determine whether the Bacon cell had commercial potential as a replacement for the lead-acid storage battery. After a year, the subcommittee judged that it did not. Nevertheless, its members developed various new justifications for continued support of research. Ellingham, the subcommittee's most outspoken critic of the storage application, believed further study could determine whether the Bacon cell could be made into a "fuel cell," a device with the potential to use hydrocarbon fuels. In the meantime, noted Rideal, then supervising the laboratory team, Bacon had an excellent track record of improving current density and the subcommittee could expect further progress over the next 15 months. There was also the attraction of supporting a novel technology of which few seemed aware and which might yet prove to be a breakthrough. It would be worth continuing work, opined the electrical engineering consultant C.W. Marshall, "for the sake of continuity" since "no one else seemed to be doing anything on the problem."[31] For much of the remainder of the project, these arguments comprised *in toto* the positions that would justify and motivate the ERA program.

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[29] Unconfirmed Minutes of the Second Meeting, Section Z, Sub-Committee F, Electrical Research Association, 28 November 1947, Bacon TS, B.127, 2.
[30] Ibid., 4-5.

Pressure to deliver results on the ERA's investment by October 1948 further cemented Subcommittee F's commitment to probe the Bacon cell's potential as a "fuel cell." This was reflected in its decision to include "electrical generation" in addition to "storage" in its descriptive suffix as well as new interest emanating from quarters of government concerned with fossil fuels.[32] The new chair for the subcommittee's fall meeting was Sir Alfred Egerton, a professor of chemical technology at Imperial College and chair of the Scientific Advisory Council to the Ministry of Fuel and Power.

A flurry of activity revealed how important fresh demonstrations of the fuel cell's high current density were to the program's political fortunes. Subcommittee F's third meeting unfolded in an atmosphere of some tension amid Bacon's report of disappointing test results owing to the delay in deliveries of new nickel electrodes. Egerton held that a formal program could not be started until the latest batch of experiments using the new electrodes had been performed. He recommended that it should be made clear to the supplier in no uncertain terms that the matter was urgent. Tests on the new equipment were imperative: if they did not come off well, an "unfavorable impression" would result. Whitehead observed that the program was entering a critical new phase in which the basic design was about to enter the "engineering stage," meaning the apparatus was on the verge of being enlarged and made more powerful.[33] This would require an influx of additional resources, something that was bound to raise questions among the ERA's constituent industries as to their interest in the project.

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[31] Ibid., 5.

[32] "Electrical generation" suggested the function of creating, rather than storing electricity, which accorded with the ERA's re-definition of the Bacon cell as an "electrochemical engine" or "fuel cell," a device expected to convert chemical to electrical energy as long as it was fed with (hydrocarbon) fuel.

A successful new round of laboratory demonstrations in the first half of 1949 broadened interest in the potential "fuel cell," raising expectations for practical applications among the British engineering and scientific community, but also sharpening the unresolved fuel question. Paradoxically, these events made the absence of any overarching research policy even more obvious. In June 1949, representatives of the Department of Scientific and Industrial Research and the Ministry of Supply attended a meeting of Subcommittee F for the first time. The ensuing debate was as fractious as ever. Reports of new achievements in the laboratory were counterbalanced by confusion over the program's ultimate goals, increasing doubt whether the technology was really was in the ERA's interest.

The meeting began, as usual, with a favorable assessment of laboratory work before the subject turned to the larger question of applications. Even at this stage, however, some association members did not appreciate that the ERA had not yet defined an application for the "fuel cell." The subcommittee chair's own inquiry to see if there was a chance that weight reduction might make development "worth while" assumed that the device was in fact being developed in the storage battery role, a role that the ERA had already rejected. This betrayed a failure to comprehend that it was not weight but the question of fuel that was the most important issue over the long term. Another subcommittee member volunteered that Rideal and Ellingham had demonstrated that making a commercial decision was impossible and recommended ending the program.

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[33] Unconfirmed Minutes of the Third Meeting, Section Z, Sub-Committee F, Electrical Research Association, 29 October 1948, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.128, 2-4.

There were also indications that the research program was relevant only to a small number of the ERA's constituent industries. Whitehead noted that the battery and accumulator manufacturers, those companies with the greatest interest in electrochemical technology, contributed relatively little to the association's operating budget. Another subcommittee member ventured that there might be no need for a research program at all, since British lead-acid battery makers had achieved a world monopoly on their four-year lifetime guarantee almost exclusively by "commercial means," meaning simple empirical methods. Whitehead then sought to downplay the link between ERA support and the practical utility of the Bacon cell. He repeated earlier statements that the association regarded its involvement with the technology as exploratory and unlikely to immediately realize "commercial value."[34]

It might seem as if this would have settled the issue. However, confronted with mixed messages and unfamiliar with the project's origins, the government representatives, particularly the Ministry of Supply official, chose to interpret the matter in the best possible light. He understood that the research involved a search for basic principles relating to a "fuel cell." Because this application offered "limitless" potential, and given the relatively small levels of funding involved, between £1,200-£1,500 per year, he believed the research should continue, adding that the Ministry of Fuel might be interested if the Electricity Authority would not supply funds.[35] This posed a dilemma for Whitehead, for the ERA was supporting laboratory work on the energy conversion component of a hydrogen-based energy storage system, the "reversible accumulator," that the subcommittee had already agreed was uneconomic in its complete form. By developing a hydrogen fuel cell without the electrolyzer and hydrogen storage systems, the research association was ensuring that the resultant technology was completely impractical for all but specially prepared laboratory demonstrations.

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[34] Unconfirmed Minutes of the Fourth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 8 June 1949, Bacon TS, B.128, 6-7.

By persisting with the program, the ERA encouraged the view that a solitary non-storage "fuel cell" was in fact feasible. In turn, this implied that some other fuel besides hydrogen would be used. Among the committee's members, only Ellingham seems to have fully grasped the position the association was now in. Bacon was making good progress but the work was "fundamental," not "applied," in the sense that it offered "no great promise of return" in the near future. If the Bacon cell was to be configured as a "fuel cell," it would be necessary to quickly determine whether the device could be run on carbonaceous fuel and air in place of pure hydrogen and oxygen. There were, Ellingham added, different kinds of high-temperature fuel cells that were better suited than the Bacon cell for such reactants.[36] Pursuing these required a completely new research program.

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[35] Ibid., 6, 8. This is equivalent to £27,000-£30,000 in 2007 currency.

A political problem loomed regarding definitions and expectations of research, one that reflected the institutional imperatives of the ERA and the disparate worldviews of Bacon and Whitehead. The latter's professional background and responsibilities at the ERA had not prepared him for an open-ended electrochemical research project of uncertain utility. Trained as a physicist at Oxford, Whitehead had received his doctorate in electrical engineering at London University. Though he straddled the worlds of science and technology, serving on a number of scientific and engineering committees, he devoted most of his career to solving practical problems relating to electrical transmission including cable ratings, telephone interference and vibration.[37]

Whitehead's position was further circumscribed by the British electrical industry's ambivalence towards the ERA. For years, it regarded dedicated scientific research in support of ongoing operations and technology development as a waste of money. Although the ERA had been founded in 1920, it did not build a dedicated laboratory (at Perivale) until 1935. The research association did not even acquire its own journal until 1956. In the mid-1950s, the electrical industries contributed only a modest annual sum of £100,000 to fund the ERA's operations; it required 10 years to raise £400,000 to equip a new replacement laboratory at Leatherhead.[38] This also reflected the relatively low priority the national government accorded the ERA vis-à-vis its research facility construction program.

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[36] Ibid., 5, 7.

[37] "Obituary: Dr. Whitehead," *Cooperative Electrical Research: The Journal of The British Electrical & Allied Industries Research Association* 1 (July 1956): 2-3. Among other positions, Whitehead was chair of the IEE Measurements Section, honorary treasurer of the Institute of Physics, joint honorary secretary of the Parliamentary and Scientific Committee and chair of the Committee of Directors of Research Associations.

[38] C.W. Marshall, "ERA and the Electricity Supply Industry," *Cooperative Electrical Research: The Journal of The British Electrical & Allied Industries Research Association* 1 (July 1956): 7-9.

Such parsimony gave Whitehead little room to maneuver. He increasingly framed the Bacon program as one of basic research, yet activities that were unlikely to yield anything of immediate commercial value were acceptable to the ERA only insofar as they contributed in some way to solving "practical" problems.[39] The difficulty was that an application had to be found very soon if the project was to continue. Bacon himself had devoted relatively little thought to this, focusing most of his energies on perfecting the power source. Shortly after the war, he had approached a chemical company for research support and found himself at a loss when the firm's executives asked how he intended to apply the technology. The "best he could say" was that the technology might be utilized in a fuel cell electric automobile using electrolytically produced hydrogen. The executives responded with derision.[40] Whitehead had also raised the possibility of such an application in the fourth subcommittee meeting. But electrical storage, the only role that appeared likely if hydrogen was used as fuel, had already been discounted, and the ERA was not funding work on an electrolyzer. The automotive application was never the subject of serious discussion within the subcommittee.

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[39] Ibid., 7. The difficulty of distinguishing basic from applied research in this context was underscored by Bacon himself. He referred to the work he was then doing on extending the lifetime of the oxygen electrode as "fundamental." Developing electrodes for a liquid electrolyte fuel cell was a difficult and intricate operation, for the devices had to be made in such a way as to allow the gaseous reactants to seep through them and contact the liquid electrolyte without allowing the liquid to "flood" the electrode. Bacon's solution was the "dual porosity" electrode: by making the side of the electrode through which gas was pumped with pores larger than on the side facing the liquid electrolyte, a pressure differential was created that facilitated the proper balance between contact and separation. This work was strongly technological and empirical in nature.

[40] Bacon, "The Fuel Cell: Some Thoughts and Reflections," 8C.

By the summer of 1949, Whitehead was beginning to have doubts about whether the project did indeed lie within the aegis of the research association. Nor was he sure what branch of industry was best suited to take up the program. Before the ERA could take further action, he indicated, a comprehensive policy had to be drafted outlining applications and objectives. There was something of a warning in Whitehead's observation that research had proceeded for three years and featured prominently in annual ERA reports in the absence of any real plan, a hint perhaps that some of the association's members might soon begin to inquire about results.[41]

As such, the ERA had to quickly reconcile the "fuel cell" as a physical phenomenon in the laboratory with its commercial requirements and demonstrate the technology's utility to its member industries. Above all, the fuel issue loomed. Yet the ERA seemed unable or unwilling to come to terms with it, likely because it had by then so heavily invested in development of a hydrogen fuel cell. In different ways, the various players had developed stakes in the program. Those subcommittee members intimately involved in the minutiae of this work, particularly Rideal, developed loyalties to it and to Bacon that overshadowed the project's larger economic and political implications. They could always point to proof of progress in increasing power density. In contrast, Whitehead became increasingly concerned with developing a suitable political justification for a program that had ceased to offer hope for tangible economic benefits. As work proceeded, so did expectations that Bacon's hydrogen fuel cell might be made to run on hydrocarbons.

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[41] Unconfirmed Minutes of the Fourth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 8 June 1949, Bacon TS, B.128, 8.

The Ministry of Supply's interest in the Bacon cell project is worth noting. As Britain's largest and most important state industrial organization, purchasing large quantities of military and civilian products, including capital goods for the nationalized electrical and mining industries, this bureaucracy had considerable influence in the conduct of state-backed civilian and military research and development.[42] The fifth meeting of the subcommittee in November 1949 well illustrates the political maneuverings that sustained momentum within the project. The initial discussion of laboratory work soon gave way to a dispute over whether the Bacon device was a storage battery or a "fuel cell" and which of a number of seemingly contradictory progress reports should be sent on to the ERA council. Ellingham, supported by Rideal, favored a report that described the Bacon device as a primary "fuel cell" over one making "an unfortunate" comparison with a storage battery.

This, however, implied the electrochemical conversion of hydrocarbons, something that Bacon was not investigating. The Ministry of Supply official then raised the issue of making hydrogen from coal, prompting Rideal to note that it would be a "considerable advance" if the Bacon cell could be made to run on coal-derived gases. At this point, Marshall remarked that such speculation was unhelpful. The ERA council, he warned, would take a dim view of misleading statements regarding impending commercial applications unless a specific application and "intention of use" was clearly stated.[43]

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[42] David Edgerton, "Whatever Happened to the British Warfare State? The Ministry of Supply, 1945-1951," in *Labour Governments and Private Industry: The Experience of 1945-1951*, eds. Helen Mercer, Neil Rollings and Jim D. Tomlinson (Edinburgh: Edinburgh University Press, 1992), 91, 102.

Somewhat defensively, Whitehead replied that he "saw no harm" in suggesting alternatives if there was some hope that the technical problems could be solved. With the Bacon cell unable to compete with conventional commercial storage batteries, Whitehead now invoked wind energy, where hydrogen supply and competition with incumbent storage technologies would not be an issue. The idea was that wind turbines would power electrolyzers producing hydrogen that could be stored and later run through the fuel cell to provide electricity during periods of calm. Admittedly, this was a niche application, but, as Whitehead noted, it supplied an answer "if someone asked why we were interested in the cell." Such a system might yet prove competitive with pumped storage.[44] Marshall again reacted skeptically, stating that it was "unwise to associate two highly speculative projects" and suggested that the cells should first be demonstrated before claims were made as to their capabilities.[45]

This prompted a further series of exchanges that broached the issue of how the project's goals related to the nature of research. This revealed vastly different understandings among the committee members of the project's scientific and technical objectives. Replying to Marshall, Whitehead admitted that the subcommittee had delayed soliciting manufacturers for their opinions until their possible interests in the project had been identified. As far as the laboratory workers were concerned, noted Bacon's co-researcher T.M. Fry, the most important consideration was to first improve the performance of the fuel cell stack itself, particularly the oxygen electrode. Rideal noted that subsequent effort could be devoted to adapting the design to use cheaper carbonaceous fuels. Whitehead then put a question to the committee: should the project proceed as Fry had indicated or as a "fundamental investigation"?

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[43] Unconfirmed Minutes of the Fifth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 29 November 1949, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.128, 5.

[44] This was the use of off-peak electricity to pump water into reservoirs for use in hydroelectric power generation.

[45] Unconfirmed Minutes of the Fifth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 29 November 1949, Bacon TS, B.128, 6.

Here, Whitehead reflected the ERA's conventional notions of the utility of research, differentiating between that which quickly yielded commercial value and that which did not. On the other hand, the laboratory team defined what Whitehead took to be a "technological" process - the construction, integration and operation of electrodes in fuel cells - as an "essentially fundamental" operation. Bacon claimed that this was a point he had made clear to the subcommittee several times in the past. Rideal qualified this further, saying the research had "prospects" of yielding fundamental knowledge. If that was the case, Whitehead responded, the program should be supervised by "academic leaders in the field."[46] This seemed to suggest that the ERA should wash its hands of the matter.

Egerton, however, thought it best that work continue on electrode development over the next six months while possible applications were discussed. For a majority of subcommittee members, the improvements Bacon had made in the current density of the cell were sufficient on their own to justify the continuation of the project. The objections of someone like Ellingham, that durability and other issues meant that it was impossible to say at this point whether the cell could actually serve any practical purpose, were irrelevant to them.[47]

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[46] Unconfirmed Minutes of the Fifth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 29 November 1949, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.128, 3,7.

The basic design of the Bacon cell was frozen in 1949 at Cambridge under the direction of G.W. Austin. The laboratory team's success in terms of current density was such that one year later, Subcommittee F decided that the Bacon cell was in fact a legitimate subject of research and worthy of continued support. This *revived* the notion of the cell as a storage device. In contrast to some of its previous gatherings, the subcommittee's November meeting of 1950 was generally free of dissent. Possibly this was due to the absence of Ellingham, but it was more than that. All issues relating to fuel remained set aside.

In front of a large assembly of invited visitors representing leading government and industrial research and development agencies including the Ministry of Supply, the Ministry of Fuel and Power, the Royal Aircraft Establishment and the ERA Council, Whitehead recounted the history of the program. True, the ERA had extended support on the basis of little more than "scientific curiosity." This investigative phase had now passed and concerted research had indicated that the device indeed had useful potential. Current density and efficiency had reached levels sufficient to entertain serious consideration of a number of applications. The subcommittee, claimed Whitehead, had determined that the hydrogen/oxygen cell could be compared with the lead acid battery in units of greater than 30 kilowatts with discharge times of between five to ten hours, and "progressively better" for higher power levels and longer discharge times.[48]

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[47] Ibid., 7-8.

The "applications" mentioned by Whitehead did not, however, relate to specific electric appliances. He used the term hypothetically, either negatively, referring to roles not presently filled by existing storage devices or, in the most general descriptive sense, "the direct electro-chemical generation of electrical energy." In neither case was it clear what the cell would actually power. While there was some interest from the government delegation, it was decidedly tepid. The chairman of the Merseyside and North Wales Electricity Board saw the Bacon cell as a potential power source for electric agricultural tractors but the ministerial representatives were less enthusiastic. The Ministry of Fuel and Power official was interested but could not fathom what the device might be used for; his colleague from the Ministry of Supply saw it as suitable for powering navigational aids in remote, inaccessible locales.[49] The ERA Council chair seized on this, remarking that the beacon application was a good place to start, for it would show that "something definite had been accomplished." The cell might later prove suitable for a wide variety of roles including traction, large-scale storage and as an auxiliary for a wind-power generator.[50]

Despite this ambiguity, or perhaps because of it, the conference ended with what amounted to a major redefinition of the nature of research on the Bacon cell, the ERA's role in this effort and expectations for the final product. The parties agreed that the project would continue with a view to long-term developments, with research focusing on "fundamental difficulties" relating to the performance of the oxygen electrode.[51] In essence, the conferees acknowledged that although the practical questions of fuel and applications central to the commercial feasibility of the Bacon cell could not quickly be resolved, this did not mean the project lacked merit.

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[48] Unconfirmed Minutes of the Seventh Meeting, Section Z, Sub-Committee F, Electrical Research Association, 17 November 1950, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.129, 3, 5.
[49] Ibid., 6.
[50] Ibid., 7.

In its current form, the device was fit only for laboratory demonstrations and seemed destined to remain so for some time. But "fundamental" research as it related to the Bacon cell was no longer seen as solely an abstract search for basic physical principles best suited for an academic environment. No longer would the project be associated with immediate commercial utility. Rather, the ERA formally recognized Bacon's "techno-scientific" understanding of the nature of the research work, which was now firmly linked with the development of technology. More accurately, attention was now shifting to the components of a device that itself needed to be a component of a larger system in order to be marketable, but on a much longer timeline than had previously been considered. While commercialization remained the ultimate goal, this was set in the indefinite future. Couched in this way, the Bacon cell project could be made to fit within the purview of the ERA.

While there was virtual unanimity within the subcommittee on these points, some members felt that the program was still too speculative. While the skeptical Marshall was won over, he emphasized that subsequent work be "associated with good engineering design." Egerton agreed that what was needed for such an accelerated program was "closer contact" between "engineering design" and electro and physical chemistry. As if to make completely clear the applied nature of the effort, the subcommittee endorsed Egerton's suggestion to maintain for the time being the existing team under Rideal's leadership at Cambridge. Further, the team would work with industry specialists from the Mond Nickel Company, who would provide expert metallurgical advice relating to the construction of porous electrodes.[52] The research team's techno-scientific turn was completed by the addition of the electrochemist R.G.H. Watson in 1951; his job was to find a way to end the corrosion of the oxygen electrode in the caustic environment of the fuel cell reactor.[53]

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[51] Ibid., 7.

Subcommittee F had begun to demonstrate a more sophisticated "techno-scientific" understanding of the Bacon cell project. In a sense, though, the effort remained an exercise in the abstract. During this period of component improvement, the ERA continued to put off the problem of how practical fuel cell power generators, comprising batteries or stacks of individual cells, would be built and how they would ultimately be applied. Macro-economic studies of fuel cell technology would not appear until the mid-1950s, when work at Cambridge began to wind down. In the meantime, new sponsors emerged to contribute funds. In early 1951, the Ministry of Fuel and Power joined the ERA in a 50/50 partnership. By 1953, they had together committed a total of £6,560.[54] The Royal Navy was also interested in the Bacon cell. It wanted to explore the device as a possible propulsion unit and experiment running it on hydrocarbons. In April 1953, the Admiralty contracted with the ERA and began to contribute funds to the research effort.[55]

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[52] Ibid., 7-8.

[53] Williams, "Francis Thomas Bacon, 21 December, 1904-24 May 1992," 7.

[54] Aide Memoire by A.P. Paton, 19 July 1955, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.143, 1. This was worth about £100,000 in 2007.

[55] Memorandum, "Admiralty Interest in British Provisional Patents 25801/56 and 25802/56," 17 August 1957, Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, 'Admiralty and C.J.B.,' B.1080, 3.

The ERA expected the Ministry of Fuel and Power to help support the laboratory work until such time as the Bacon cell was ready to be taken up by an interested party in industry or government. But this was complicated by the fact that the technical requirements for such a transition to occur were not, indeed, could not be, clearly stated at the outset. The work at this stage was focused strictly on individual electrodes, or half cells, and on single cells, combining an anode and a cathode, not the stacks of full cells comprising a complete system. As Marshall had warned during the subcommittee's seventh meeting, such tests as had been performed were very short, and little was known about the relationship between current density and durability.

The Bacon Cell Makes a Splash

In the early 1950s, the Bacon cell was still too primitive for potential customers to formulate requirements and identify roles. The ERA had set the technology on a path where the best possible outcome was a fuel cell energy conversion system that lacked the capability to produce and store hydrogen. But though the project had been programmed so that no level of success in the laboratory could alter the device's dependence on this difficult and costly fuel, potential suitors were made to believe that it could be run on petroleum-derived hydrogen produced by industry. In the meantime, the "fundamental" technology program progressed, accruing some prestige and attracting attention. The Cambridge team's production of a new durable oxygen electrode in early 1953 created a stir in engineering circles, notably in the United States. In April, the Office of the Naval Attaché of the U.S. embassy in London asked the ERA for permission to allow an American scientist to visit the Bacon group at

Cambridge. Whitehead gave his approval on condition the Americans respect the confidentiality agreement between the DSIR and the Embassy. In a postscript, Whitehead felt it necessary to warn the Americans to be "very cautious" about the oxygen electrode, "the benefits of which we must secure for this country."[56]

By 1954, the uneasy balance between the physical realities of the laboratory technology and external perceptions of what the Bacon team had accomplished was reflected in an epistemological divide. With the ERA unable to identify a clear role for the Bacon cell as it was then configured beyond the niche role powering a navigation beacon, even members of the research team developed differing opinions concerning the object of work. In an article published in *Research* in January 1954, Watson indicated that the initial goal was to develop the Bacon cell as a *storage* device. He held out the possibility that it might later be modified into a fuel cell consuming hydrocarbon-derived gases. Indeed, Watson saw the technology as a kind of universal energy converter, a modern "philosopher's stone."[57] Bacon, on the other hand, was skeptical about altering the device to run on hydrocarbons, believing a hydrogen fuel cell could stand on its own merits.[58]

It is important to note that in its then-current state, the Bacon cell could not be readily adapted for commercial use in either form. Nevertheless, as Bacon prepared to publish an article in the *British Electrical and Allied Manufacturers Association Journal* in early 1954, its editor insisted Bacon revise the paper's title so that it referred not to a "Hydrogen-Oxygen Cell" but a "Hydrogen-Oxygen Fuel Cell," in order to create more interest.[59] This article introduced the Bacon cell to the larger industrial community.

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[56] George Szasz to Whitehead, 15 April 1953; Whitehead to Szasz, 20 April 1953, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.136. Szasz invoked a previous visit to Bacon by a Dr. K.R. Eldredge at Cambridge as a precedent in asking for Whitehead's approval for a visit by an American physical chemist named Ralph Rogers. Rogers appears to have had military ties, having attended a recent conference on defence research in Britain. Whitehead responded that he had no objections to another visit by Dr. Eldredge, but noted, without mentioning Rogers by name, that subsequent ERA patents would be invalidated if any exchange of information occurred with individuals not covered by "security agreements."

[57] R.G.H. Watson, "Electrochemical Generation of Electricity," *Research* 7, no. 1(January 1954): 34, 39-40.

[58] Bacon, "Research into the Properties of the Hydrogen-Oxygen Fuel Cell," 12.

One of the consequences of the semantic confusion over the nature of the Bacon fuel cell was that petroleum concerns began to evince interest. That year, a 150-watt Bacon cell was exhibited for the first time in London. In May 1954, Whitehead informed Bacon that he had been approached by a number of companies regarding the possibility of running the cell on the waste hydrogen byproduct of "various new processes" in the oil industry. The fact that one of the interested parties was American, stated Whitehead, meant that drafting a techno-industrial policy for the Bacon cell had become even more urgent.[60] In June, Bacon's article appeared in the *BEAMA Journal*, sparking further interest. In September, Whitehead asked Bacon to meet with representatives of the Anglo-Iranian Oil Company in order to investigate the possibility of joint development of commercial applications for the hydrogen-oxygen cell.[61]

These new commercial contacts made the issue of fuel more critical than ever, yet the subcommittee remained largely sanguine. At its eleventh meeting in May, Whitehead, pleased with the improvements in current density, asked for criteria in considering specific applications. Fox replied that he believed that these problems would be solved "elsewhere," presumably by industry. Nevertheless, he added, it would be possible to extrapolate engineering design calculations for a multi-cell battery from the operation of a two-cell rig set up in the laboratory, which had given no problems thus far. Of the conferees, only Ellingham pursued the point. When he inquired about applications, Whitehead was noncommittal, repeating the three general fields he had previously outlined of traction, storage and generation, adding that he didn't believe hydrogen would be used for power generation. Fox sought to qualify this remark, noting that although "other gases" had been considered, hydrogen was being used in laboratory tests so as to provide the "best possible conditions" for cell operation.[62]

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[59] Bacon, "The Fuel Cell: Some Thoughts and Reflections," 9C.
[60] Whitehead to Bacon, 20 May 1954, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.139.
[61] Whitehead to Bacon, 10 September 1954, Bacon TS, B.140.

This sparked a debate over how hydrogen would be supplied for large-scale operations. Ellingham immediately responded that if the cell could not be converted into an electrolyzer, "separate means" would be necessary, prompting a query from a subcommittee member as to whether an economic study was now justified. Interpreting this as referring to the hydrogen-oxygen cell itself, not to the feasibility of using hydrogen as a fuel on any scale, Egerton responded that such a study could not proceed until cell lifetimes were known.[63] The problem was that the Cambridge laboratory had not yet begun this kind of testing on either its single cells or the two-cell rig, let alone multi-cell stacks, the latter being a task Fox suggested was a job better suited for industry, not academe.[64] Egerton's circular statement appeared to have set any direct ERA role in drafting such a study well into the future.

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[62] Unconfirmed Minutes of the Eleventh Meeting, Section Z, Sub-Committee F, Electrical Research Association, 24 May 1954, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.131, 5.

[63] Ibid., 5.

A review of whether there was indeed a demand in the British economy for a hydrogen fuel cell of any type did not, however, necessarily depend on lifetime test data produced by the Cambridge laboratory. All that was required was knowledge of whether any British industries or government departments were willing and able to use hydrogen. Given that the ERA was the research arm of the British electrical industry, it might have been expected that it or one of its members would have had an interest in conducting such a study before any money was spent on research. The political protection such a study would have afforded in case the research proved fruitless seems a compelling reason on its own. In the event, the reverse had occurred. Eight years after the ERA had begun to support the Bacon team, the first moves to begin an economic appraisal were made, not by the ERA, but by the British General Electric Company (GEC).

In August, Whitehead approved the transfer of project data to aid this effort.[65] This chain of events indicates that government and industry, through the ERA, viewed the institutional responsibilities of research and development in highly reductive terms. Although the ERA's mandate was to support research of value to the various industries it represented, it increasingly viewed its stake in the research team at Cambridge in narrow, self-referential terms. It had groomed a sophisticated techno-scientific research community tasked with specialist goals and conditioned to a cycle of success and funding. Both sponsors and researchers repeatedly put off the question of who would want to use the technology they were developing. That they were able to do so and still maintain the program's momentum is indicative of the impression preliminary prospective tests made on them. The hope that the Bacon cell might yet make obsolete the internal combustion engine and bring about a revolution in energy technology was too attractive to relinquish easily.

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[64] Fox added to the confusion by remarking that such an economic analysis could begin once it could be *assumed* that cell life was between 8000-10,000 hours.

[65] Paton to Bacon, 5 August 1954, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.140.

Withered Fledgling: The Making of a Technological Orphan

Despite the growing publicity that surrounded the Bacon cell after 1954, some observers were having doubts about fuel cell technology. In October, a retired National Carbon Company researcher noted in the *Journal of the Electrochemical Society* that the economics of the fuel cell were "confused" and that the technology might never become competitive with heat engines.[66] Powerful figures within the British science and engineering establishment also were skeptical. In an address to the Royal Society in November, Lord Halsbury, the first managing director of the National Research Development Corporation, doubted whether fuel cells could much improve on the efficiency of coal-fired thermoelectric plants.[67] In an article published in *Research* in December, Halsbury criticized the British research and development community's "romantic" desire for technological spectaculars that obscured underlying flaws, a tendency apparent in the Bacon cell program. It was not that a lack of fundamental knowledge was retarding practical progress. Rather, Halsbury indicated, years of research had revealed no practical solution. The technical merits of the fuel cell were simply "lacking." Indeed, if the best specialists in the field were now currently receiving adequate support, little more could be done.[68] This was a serious indictment of the ERA/MoFP program.

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[66] George W. Heise, "Research in Industry," *Journal of the Electrochemical Society* 101, no. 12 (December 1954): 293C.

[67] "Extract from Address by the Earl of Halsbury at the Royal Society of Arts 1/11/54 entitled Science Fiction and Economic Fact," undated correspondence from Paton to Bacon, Bacon TS, Section B, Research and Development, ERA/University of Cambridge, Correspondence, B.140.

As 1955 progressed and the fuel and application issues remained unresolved, Whitehead began to realize the laboratory work had come to a crossroads. On the hydrocarbon front, negotiations with the Anglo-Iranian Oil Company came to naught, though other firms including Shell and Esso expressed some interest. This left the electrolyzer, long off the ERA's agenda, as the only option for fuel production and thus early commercial development of the fuel cell. It soon became clear to the ERA that this would not be a simple matter. That year, the Wharton engineering firm had approached Bacon and then the NRDC when it realized that developing an electrolyzer represented a considerable investment.[69] The NRDC then contacted Whitehead for advice.

The record of correspondence does not make clear if Whitehead made an explicit reply. It is, however, clear that he was of two minds on the subject. In a June 1955 letter to Bacon, Whitehead was noncommittal. Privy to its details ahead of its release, he knew the GEC report gave a negative assessment of industrial applications for the hydrogen-oxygen cell. Industry skepticism with fuel cells made building a case for proceeding with the electrolyzer more difficult. Whitehead concluded that the ERA would have to review its support of the entire program.[70] It was something he was reluctant to do. In a letter to Bacon in September, Whitehead stated that although he felt it was unlikely that Lord Halsbury would take any separate action on the electrolyzer, there was one last hope, the possibility that the electrodes that had been developed could be used to build a suitable electrolyzer.[71]

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[68] Earl of Halsbury, "Strategy of Research," *Research: Science and Its Application in Industry* 7 (December 1954): 480.

[69] Aide Memoire by Paton, 19 July 1955, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.143, 3.

[70] Whitehead to Bacon, 20 June 1955, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.142.

Almost from the first, the ERA had decided to pursue the Bacon cell strictly as an energy converter without the hydrogen production and storage equipment. As a result, it created a technological orphan. The GEC report concluded that the economic feasibility of the entire Bacon cell project turned on the production and storage of hydrogen. With laboratory development substantially complete by late summer, the report indicated that there were scant roles for a fuel cell consuming such an expensive fuel and few organizations were willing to take up the project. Only in electric railcars were there economic possibilities for the Bacon cell.

By this time, Whitehead was fully aware of the limited scope of development. The Bacon cell could not generate power on a large scale unless it could be made to employ cheap carbonaceous fuels.[72] Now the ERA was considering special roles for the Bacon cell on a much smaller scale involving the storage of electricity produced by wind power.[73] The association had studied this application since at least 1949, but as an ERA report of January 1956 indicated, it depended on advanced, affordable high-pressure electrolyzers and gas storage methods.[74]

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[71] Whitehead to Bacon, 13 September 1955, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.144.

[72] Whitehead to T.E. Allibone, 10 November 1955, Bacon TS, B.144. In this letter, Whitehead admitted that he had only a lay knowledge of electrochemical engineering.

[73] Whitehead to J.N. Agar, 24 June 1955, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.142.

[74] "The Possibilities of the Bacon Hydrogen-Oxygen Cell When Used in Association with Wind Power," Section Z, Subcommittee F, 20 January 1956, Bacon TS, Section B, Research and

As Whitehead indicated to Bacon, the electrolyzer was too expensive even in this application, throwing "everything out of balance."[75] In a way, the point was moot because this vital technological sub-system had never been the subject of a specific ERA development program. Subcommittee F seems to have believed that the Bacon cell could simply be "reversed," or turned into an electrolyzer, with relatively minor modifications. In fact, both it and the hydrocarbon fuel cell research were major undertakings in their own right, requiring wholly new programs.

The contradictions in the ERA's policy of supporting "fundamental" research on one component of a technological system of unclear utility for its industrial clients now became evident. Because the research had been completed and the cell was "out of the laboratory," the ERA could not continue the program for more than a few months without industrial support. Industry, however, was uninterested. Whitehead's appeal to T.E. Allibone of Associated Electrical Industries for aid in salvaging the work had something of a ring of desperation to it. He stated he was in a "great difficulty" as to whether the situation warranted a further investment of resources. The problem was that the ERA could retain personnel only for either basic research or applied research "which industry is willing to absorb."[76] In effect, Whitehead was saying that through its refusal to support applied work at the ERA, industry was abandoning the matter. The Bacon cell was in developmental and institutional limbo.

Development, Electrical Research Association/University of Cambridge, Reports, 'H-O Cell Reports II,' B.110, 2.

[75] Whitehead to Bacon, 11 November 1955, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.144.

[76] Whitehead to Allibone, 10 November 1955, Bacon TS, B.144, 2.

Only "special circumstances" could warrant the use of costly gaseous hydrogen and only the Admiralty had such requirements.[77] There was speculation the Bacon cell might be used as a submarine powerplant but this would have been of little comfort to Whitehead, head of an organization dedicated to supporting the British electrical industry. By the end of the year, the Ministry of Fuel and Power withdrew its support from the project, concluding, like the ERA, that the laboratory work was complete and the Bacon cell was ready for commercial exploitation.[78] Without commitments from industry, however, the Cambridge team could be kept together for only a few more months. The prospect of the breakup and loss of the research team before a white knight could be found to "adequately exploit for British industry the knowledge they have acquired" was, said Whitehead, a "great pity."[79] Given the years of work and tens of thousands of pounds expended, it may be fair to assume that the professional consequences for Whitehead and others connected with the project could well have been serious.

The January 1956 meeting of Subcommittee F illustrated the degree to which the research program had become uncoupled from industrial requirements over eight years, revealing the chasm between technological feasibility and cost-effectiveness. The laboratory teams and the industrial analysts were two solitudes, each speaking their own languages conditioned by their interests and experience and often talking past each other. To the assembled subcommittee, GEC officials reviewed the company's assessment of the Bacon cell project. They concluded that while storage was not currently a "commercial proposition," they did not rule out the possibility that further "performance increases" might make it so.[80] This underscored the company's unfamiliarity with the Bacon cell project and its reliance on pure hydrogen, the prime reason it was economically unattractive. Further performance improvements would not change this basic fact.

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[77] Ibid., 1.
[78] Bacon to Lord Halsbury, 23 February 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.273.
[79] Whitehead to Allibone, 10 November 1955, Bacon TS, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Correspondence, B.144, 2.

Nevertheless, this gave Bacon an opening. He responded that his fuel cell, when integrated with an electrolyzer, seemed promising. Dr. Fox, supervising work at the Cambridge laboratory, reinforced this implicit vision of a hydrogen economy, stating at one point that large-scale hydrogen storage was relatively unproblematic compared with lead-acid battery storage.[81] The GEC officials then elucidated the point: an electrolysis system compared unfavourably with an internal combustion engine system owing to higher capital costs. Still, they held out hope for the Bacon cell, claiming that it could be most "profitably exploited" if used as a "fuel cell" instead of a storage device in the transport role running on coal-derived gas and air.

This merely recapitulated the ERA's own long-standing position. The paradox was of course that such a system was a fiction. It did not remotely describe the technology the ERA and Bacon had been developing. From the beginning of his researches in the 1930s, Bacon had expressly sought to avoid problems posed by fuel cells using acidic electrolyte. Unlike alkaline fuel cells, acid systems were not contaminated by carbon dioxide and were therefore more capable, in principle, of using "dirty" fuel gases derived from cheap carbonaceous substances. In theory, this made the fuel problem more manageable than in the case of alkaline fuel cells, which required costly pure hydrogen. However, acidic fuel cells using carbonaceous fuels not only had lower performance than hydrogen-fuelled alkaline fuel cells but also were more expensive on a unit per unit basis because they needed platinum to catalyze the electrochemical reaction.[82] Further, the GEC tied progress in the performance of fuel cells in automotive applications to that in internal combustion engines, invoking an ever-shifting standard that made it impossible to ever draw even with the established technology. This became a characteristic feature of fuel cell research and development when its centre of gravity shifted to the United States in the 1960s.

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[80] Unconfirmed Minutes of the Twelfth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 24 January 1956, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.132, 6.
[81] Ibid., 7.

In essence, the GEC report declared the project uneconomic. From the moment hydrogen was produced, by any means, no matter how technologically advanced, a Bacon cell-based power and transportation network lost money in competition with the incumbent system. The existing infrastructure had the insuperable advantages of mature power technologies that were constantly being improved on an immense scale and, for the time being, a plentiful supply of cheap fossil fuels. Yet while the GEC report rejected the Bacon cell as it was then configured, it did not rule out the possibility that future research might one day make it economically viable, holding out hope that there might be a role for it in railway traction. This illustrated once more how different actors had different expectations for fuel cells and their applications.

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[82] It is possible that British General Electric was choosing a diplomatic way of closing down the program. On the other hand, given that the operating dynamics of all types of fuel cells were not well understood at that time, as well as the fact that the GEC would have had an interest in exploiting research the electrical industry had funded, the company may well have believed the Bacon cell could be adapted to use carbonaceous fuels.

The GEC's reluctance to couch the fuel issue in the starkest possible terms stemmed from its awareness of possible future technological developments and the limited supply of fossil fuels. These unknowns meant the *components* of the system under discussion, mainly the fuel cell but also the electrolyzer, still had potential. Exactly what this meant in terms of research and development was unclear as long as internal combustion engines and steam and gas turbines continued to be made more efficient and carbonaceous fuels remained cheap and plentiful.

Nevertheless, the GEC's equivocal analysis allowed the project's various participants to draw some measure of solace. Rideal, now the chair of Subcommittee F, believed the company had presented a case for the locomotive application. Professor Fox was relieved that the GEC had taken his suggestion to review only the current state of the art, not possible future developments. The representative of the Ministry of Fuel and Power directly contradicted the findings of GEC by declaring the Bacon cell (apart from the electrolyzer) feasible, while the DSIR representative held out hope that funding might be provided for research on the electrolyzer, if the subcommittee so desired.[83] Rideal and Fry concluded by urging action on electrolyzer development as part of a long-term project.

This begged the question of the nature of the entire technology effort. Given that it had taken 16 years to bring the Bacon cell to this point, how had it been possible to conceive it in isolation and not as part of a system from the outset? The answer lies partly in the assumptions of fuel cell capabilities developed in earlier rounds of prospective testing. In an economy where increasingly powerful new electrical appliances with large appetites for power were rapidly proliferating, high performance power sources were increasingly in demand. High current density thus became the *lingua franca* of the industry fuel cell research and development community. Conversely, electrolyzers *used* current to produce pure oxygen and hydrogen only in specialist roles in the chemical and petrochemical industries. Despite their similar technological lineage, the fuel cell and the electrolyzer were culturally estranged. For both, but especially the latter, the proper institutional homes at this stage were unclear.

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[83] Unconfirmed Minutes of the Twelfth Meeting, Section Z, Sub-Committee F, Electrical Research Association, 24 January 1956, Bacon TS, Section B, Research and Development, Electrical Research Association/University of Cambridge, Agendas and Minutes of Meetings, B.132, 8.

Far from resolving matters, the GEC report seemed to complicate them. By February of 1956, the ERA and the Admiralty were providing only nominal support as the project was closed down and Bacon's team began to disperse. Future prospects for the Bacon cell appeared bleak. While the GEC held that the only role for the Bacon cell as it then existed was in the terrestrial storage application in railway traction, it also provided what amounted to two poison pills. The project required the electrolyzer, a non-starter, and the GEC refused to sponsor development work without the support of the Admiralty.[84] Naturally, the Royal Navy's requirements differed significantly from those in civilian rail traction. Further complicating matters was the electrical industry's increasing preoccupation with nuclear-related research, resulting in a shortage of qualified technical staff available for fuel cell work.[85] In

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[84] Bacon to Halsbury, 23 February 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.273.
[85] Bacon to Halsbury, 12 June 1956, B.273.

May, Bacon's hopes were dealt a further blow when the Central Electricity Authority categorically rejected his request for support.[86]

It was at this point that the National Research Development Corporation began to emerge as the leading contender to house the ERA's technological orphan. Bacon made the initial overture in a 23 February letter to Lord Halsbury and in subsequent correspondence outlined his near-term macro-economic plan for his invention. Hydrogen-oxygen batteries would power railcars using hydrogen produced by electrolyzers drawing power from the existing electricity grid during off-peak hours. This would also provide a good base load for the new nuclear power plants.[87] By late spring, the NRDC had tentatively committed to supporting further research on the Bacon cell.

The experience of the ERA, the Ministry of Fuel and Power and the various research teams with which Bacon had worked at Cambridge revealed distinct techno-scientific cultures, each with disparate assumptions of and expectations for the research program, each seeking to interpret in the most favorable light the body of work that they had together created. On the one hand, the growing personal satisfaction of laboratory researchers in producing ever more sophisticated electrodes and primitive fuel cells as they gradually gained the confidence of an important fraction of the research and development community underpinned a strong sense of professional identity and vindicated long-held beliefs. Theirs was a culture whose members were paid to solve sets of problems strictly circumscribed by their research and development paymasters.

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[86] Sir David Brunt to Bacon, 15 May 1956, Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, Ministry of Fuel and Power/Ministry of Power, British Electricity Authority/Central Electricity Authority, B.1164.

[87] Bacon to Halsbury, 8 March 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.273.

This was so because the goals of the industrial sponsors were initially far less-well defined than those of the principal investigators. The ERA's original motivation had been to probe the possibility that the Bacon cell might make a revolution in energy production. However, as research and development administrators, not electrochemical specialists, they were never able to directly link the laboratory work with the needs of industry. Thus, they did not closely examine the socio-economic implications of the Bacon cell until the arbitrary threshold demarcating the boundary between "laboratory work" and industrial engineering was about to be crossed. Only then did industry analysts begin to realize that the *sine qua non* for the adoption of the Bacon cell on a commercial scale was the construction of a hydrogen economy. The ERA had failed to see at the outset that the price to fully realize the revolutionary potential of the fuel cell was a new industrial revolution, one British industry was hardly willing to make. Even at this point, however, neither the industrial nor the laboratory communities seemed to fully understand the social and technical implications of their joint creation. The experiences of the ERA would be repeated by the NRDC.

Sheltering the Homeless: The National Research Development Corporation as Institutional Foster Parent

The National Research Development Corporation's assumption of responsibility for the Bacon cell project in 1956 was logical, for, in a sense, it represented the only remaining institutional avenue in Britain for continued work on the technology. Established by parliamentary legislation as an independent public body through the

Development of Inventions Act of 1948, the NRDC was designed to exploit innovations developed with public funds. Originating as part of the post-Second World War industrial reconstruction drive, the corporation was intended to complement the Department of Scientific and Industrial Research (DSIR), fulfilling the "applied" or "development" aspect of government-backed research and development. So that there was no mistaking the NRDC's mission, the conjunction between "research" and "development" was dropped from its formal title. As a "public body," funded by the state and staffed by members appointed by the Board of Trade, the NRDC was supposed to function as a bridge between science and industry, transforming fundamental knowledge produced with public support into applications for use by private industry.[88]

The NRDC's constitution called for the support of inventions that were "not being developed or exploited, or sufficiently developed or exploited."[89] The organization was also barred from seven military-related technologies, including atomic reactors and gas turbines, then the locus of government-backed research and development. The Bacon cell fit these criteria.

In other ways, however, the NRDC's motives in supporting this technology were less obvious. Less than 18 months previously, its managing director, the Earl of Halsbury, had issued a stinging indictment of the entire fuel cell effort. Nevertheless, he had responded positively to Bacon's inquiry, stating somewhat cryptically that he had always wanted to support Bacon's work "if need arose."[90] But in fact the Bacon cell did not meet all of the corporation's additional requirements. The invention had to be of "sufficient national importance" to justify the expenditure of public funds. Candidates had to be "technically sound," "industrially useful" and have commercial potential that was clearly in the national interest.[91] Further, the NRDC was designed to operate according to conventional market principles. It existed to make and help make money, both for itself and for its clients in the broader economy. It had no in-house research and development capability. Instead, its constitution directed it to seek profits from its investments by selling licenses for the technologies it helped develop.[92] Corporation planners envisioned entering into partnerships with "industrialists" who were prepared "take the ordinary commercial risks of putting a new product on the market."[93]

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[88] S.T. Keith, "Inventions, Patents and Commercial Development from Governmentally Financed Research in Great Britain: The Origins of the National Research Development Corporation," *Minerva: Review of Science, Learning and Policy* XIX, no. 1 (spring 1981): 113, 117. This is an excellent example, contra Edgerton, of the institutional and organizational effects of linear thinking in science and technology policy-making.

[89] *An Introduction to the National Research Development Corporation* (London: Waterlow & Sons, 1956), 1.

The NRDC's expectation that it would be dealing in "normal" marketplace relationships clashed with an inherent contradiction in its mandate. Halsbury himself had wondered whether industry had missed "enough good inventions" to allow the NRDC to "be able to make a living of developing them."[94] There were strong economic and technical reasons why the Bacon cell was a technological orphan. The hydrogen fuel cell without an electrolyzer was technologically sound in the laboratory context, but British industry would not use it as it was then configured. As the NRDC wrestled with the task of seeking support for an orphan technology that supposedly served the national interest, a prospective American foster parent, the Patterson-Moos division of the Universal Winding Company, stepped forward in spring of 1956.

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[90] Halsbury to Bacon, 28 February 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.273.

[91] *An Introduction to the National Research Development Corporation*, 7.

[92] Ibid., 4.

[93] Ibid., 9.

[94] Halsbury, *Research* 7, 480.

While Bacon continued to seek British sponsors throughout the spring and into the summer of that year, the ERA and the NRDC had been negotiating the licensing of patent rights to the American firm, probably since the spring.[95] During this period, Bacon made known his concerns for the electrolyzer to Halsbury.[96] The NRDC was aware of the necessity of a combined system; Halsbury's letter confirming support had explicitly referred to Bacon's "cell/electrolyzer."[97] As negotiations over transfer of ERA ownership of the apparatus stretched into the fall and winter of 1956 and into 1957, the status of Bacon's research arrangement with the NRDC remained unresolved. Bacon himself decided to abandon his work on electrolyzers when, in a separate development, the Swiss chemical firm Lonza introduced a commercial industrial model.[98]

Progress was further dogged by delays in determining the British research and development contractor that would lead the Bacon cell project as well as licensing of patents. In the fall of 1956, Bacon entered into a three-year agreement with the NRDC but it was not until well into 1957 that the corporation selected the engineering firm Marshall's of Cambridge, led by J.C. Frost. The negotiations for the licensing of the Bacon patents proved more complex. This revealed the incommensurability in the positions of the British and American negotiating teams in their assumptions and expectations of how best to develop the fuel cell that turned on their respective understandings of the marketplace.

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[95] Bacon to Halsbury, 12 June 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.273. Bacon was not privy to the circumstances leading to the initial negotiations. By June, he had learned though channels of the ERA's involvement, but not that of the NRDC, until Halsbury responded to him in a 14 June letter.

[96] Bacon to Halsbury, 12 June 1956, Bacon TS, B.273. Bacon wrote, with a conspiratorial air, that he had knowledge the Admiralty was moving in this direction, letting Halsbury know he was passing along this information "confidentially." He also mentioned an electrolyzer built by the Lonza Corporation in a 23 July letter.

[97] Halsbury to Bacon, 5 September 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.274.

[98] F.T. Bacon, "Details of Research and Development Work for the Hydrogen-Oxygen Cell, Leading up to the Construction of a Unit of About 10 kW," 16 January 1957, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.275.

The NRDC, a state entity that was explicitly charged with promoting non-military technologies unwanted by British industry and that was guided by liberal market assumptions, had chosen a partner with the military as its sole prospective client for the Bacon cell. While Universal Winding was largely concerned with textile machinery, its Patterson-Moos subsidiary was heavily involved in military research and development. As such, when Bacon and NRDC representatives visited the New York headquarters of Patterson-Moos in March 1957, the conditions under which the proposed technology transfers would take place were at odds with the NRDC's expectations and, indeed, its constitutional requirements.

Patterson-Moos' sole fuel cell contract at that point was with the United States Air Force, signed in February, and the company was supplying a variety of "working models" of hydrogen-oxygen cells, primarily for exploratory research purposes. Further, all the firm's potential additional customers were other branches of the American military. It anticipated subsequent contracts from the Air Force, Navy, and the Army.[99] These cells were to be militarized, optimized for the particular requirements of each sponsoring armed service. These differed considerably from the British civilian applications. For example, the Air Force specification called for three classes of plant with far shorter running times than envisioned by Bacon, ranging from six hours for a 750-watt unit to 30 days for a 1.5-kilowatt unit.[100] Interestingly, at almost the same moment the American military had begun began paying close attention to the Bacon cell, another military institution, the Royal Navy, determined that the technology did not meet its requirements. On 31 March, the Admiralty terminated its involvement in the project.[101]

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[99] Minutes of Meeting at Patterson-Moos Division, Universal Winding Company, N.Y., 15 March 1957, Bacon TS, B.275, 1.

Universal Winding also conflated the intellectual property and economic interests of the respective parties, promising a kind of free trade in fuel cells. A letter by the company's executive vice-president Paul P. Johnson to the NRDC began magnanimously. The American market would be open to British-made goods containing innovations jointly developed by the partnership. However, in the best interests of both parties, Universal Winding wanted an exclusive license to manufacture Bacon cells in the United States. A non-exclusive license, conversely, would inhibit the fullest possible exchange of information between the parties because Universal Winding could not risk the diffusion of innovations to its American competitors as a result of the partnership.

Johnson promised what seemed like a quid pro quo. He wanted as much technical data as possible from the British side in order to develop the military applications. In addition, explained Johnson, the company intended to "carry on our own technical and market development." This would enable Universal Winding to uncover "needs and requirements" that could aid the British in their efforts to integrate the fuel cell into their home market.[102] Here, the firm seemed to distinguish between military and civilian markets in the U.S. Indeed, this is how the NRDC interpreted the proceedings of the 15 March meeting.[103]

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[100] Ibid. The specific applications that the U.S. Air Force envisioned for these devices was not made clear to the conferees, or at least to the British party. The minutes of the meeting state only that the Air Force contract was not classified, "though its uses may be," without elaborating.

[101] Memorandum, "Admiralty Interest in British Provisional Patents 25801/56 and 25802/56," 17 August 1957, Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, 'Admiralty and CJB,' B.1080, 1.

While the NRDC remained rhetorically committed to the official position on supporting only non-military applications, this was increasingly at odds with reality. When in the spring of 1957 the U.S Army proposed that a scientific liaison be appointed to work with the Bacon team, the NRDC claimed that the corporation's interest in fuel cells was "essentially commercial."[104] In fact, stated a corporation secretary, any kind of military development fell "outside our terms of reference."[105] The NRDC's purpose was strictly to bring fuel cells to the point of demonstrating "satisfactory performance" before licensing for commercial manufacture, a task that recalled the role of the ERA.

However, the British team had been aware since March that Universal Winding's only contract at the time was a military one and that all future prospects lay with the various U.S. armed services.[106] It also could not have failed to note that the institutional affiliations of the outside representatives attending the joint conference on hydrogen-oxygen cells in March were overwhelmingly military.[107] Apart from the NRDC and Universal Winding staff, all of the invitees had direct or indirect links to the armed forces. It was also highly questionable whether the "needs and requirements" of the commercial fuel cells Universal Winding claimed to be planning for the American market would have met those in the United Kingdom, which had a significantly different urban transportation and energy infrastructure.[108] The resulting uncertainty regarding the kinds of markets that were being targeted and the ways this would shape potential applications and technological requirements meant that the research and development relationship between Patterson-Moos and the NRDC remained undefined throughout 1957 and into early 1958, a period during which negotiations on the licensing agreement continued.

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[102] Paul P. Johnson to D. Hennessey, 4 April 1957, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.276.

[103] Letter to Paul P. Johnson, 19 March 1957, unsigned copy (probably from D. Hennessey, the chief NRDC representative at the 15 March meeting in New York), Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.275.

[104] F.M. Baumgardner to D. Hennessey, 25 June 1957, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.277. Anthony Moos, the co-founder of the Patterson-Moos Division of Universal Winding and the individual who had initiated the company's relationship with Bacon, had discussed the matter with Baumgardner and endorsed his suggestion. This was further evidence of the firm's ties with the U.S. armed forces and the degree of military support backing its interest in fuel cells.

[105] Hennessey to Baumgardner, 2 July 1957, Bacon TS, B.277.

[106] The NRDC and Bacon had been aware of the U.S. Air Force's interest in Bacon's work since at least November of 1956. A representative from the Air Research and Development Command offered Bacon the possibility of direct participation in the Air Force program under a "contractual

The transfer of technology from the British to the American techno-scientific cultures was further complicated by disparate design conceptions as well as the problem of defining institutional spaces for a device for which there was still no clear application and which had not yet undergone thorough testing. This issue concerned a

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arrangement." With negotiations with the NRDC far from resolved at that point, Bacon evinced little interest in the consequences of U.S. military sponsorship. In a letter to Hennessey, the NRDC official then responsible for the fuel cell file, Bacon stated that he had "no idea" what application the Air Force envisioned but thought it worth looking into as the armed service probably had "unlimited finance;" Bacon to Hennessey, 8 November 1956, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.274.

[107] Memorandum by Albert F. Bird, 28 March 1957, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.275. This seems to refer to a meeting separate from the 15 March gathering in New York as part of the British team's March 1957 U.S. visit. Of the 13 listed attendees, seven had military ties. The Office of the Assistant Secretary for Defense Research and Engineering, the Bureau of Aeronautics, and the Bureau of Ships were each represented by teams of two representatives. The Office of Naval Research sent one advisor. The remaining conferees were representatives of the NRDC, the Patterson-Moos Division of Universal Winding and the British Joint Services Mission.

[108] The incompatibility of British and American requirements for fuel cells would dog relations between the NRDC and its U.S. patent licensees throughout the 1960s.

debate over precisely what was to be transferred: pieces of finished technology, namely electrodes, or a technology manufacturing process. The NRDC wanted to supply electrodes and retain intellectual control of the manufacturing process, while Patterson-Moos wanted to build their own. Moreover, the British side had no cells to test the electrodes Patterson-Moos wanted and the NRDC did not want to send the Americans untested electrodes.[109]

The problem was exacerbated by the vagueness of the Americans as to their exact requirements. With a licensing agreement still not yet in place, Patterson-Moos was pushing for the NRDC's electrode "recipes" or the manufacturing blueprints, information the British team was determined not to release in the absence of a formal agreement.[110] By early 1958, the NRDC had delivered electrodes to the United States, but the Americans struggled to adapt the British technology. They were having particular difficulty regulating the gas-electrolyte pressure to prevent liquid from seeping into the electrolyte. The British team suspected that Patterson-Moos engineers were improperly assembling its electrodes.[111]

By the summer of 1959, work on a 40-cell 6-kilowatt model was well advanced at Marshall's Cambridge workshop. The Anglo-American fuel cell partnership was now entering a new phase, as the NRDC mandate of transferring Bacon cell technology to industry neared fulfillment. The American company ordered two 2.5-kilowatt units from the NRDC at a cost of £6,200 apiece and Moos hinted at the prospect of more to follow over the next two years. He asked whether the Cambridge workshop was going to retain its capacity to manufacture electrodes to meet these possible requirements.[112] The Anglo-American fuel cell partnership moved into a new phase. The American giant United Aircraft Corporation entered into a joint fuel cell research and development agreement with Patterson-Moos, then known as Leesona Moos, and licensed the Bacon cell from the NRDC with a view to adapting it for aerospace applications.[113] This formal bifurcation of institutional roles in technology development along such linear lines would be emulated by other sponsors of fuel cell development in the U.S. in the 1960s and early 1970s, reflecting the assumptions that engineering and fundamental research were mutually exclusive and that fuel cell development could be facilitated by the concentration of professional expertise in discrete institutional spheres.

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[109] Hennessey to Anthony Moos, 6 November 1957, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.279.

[110] H.J. Crawley to Bacon, 21 November 1957, Bacon TS, B.279. Electrode recipes for dual-porosity electrodes indicated the pressures necessary for compacting nickel powder into disks and the times and temperatures needed to bake them in such a way that only the jagged outer edges of the tiny metal crystals fused together, leaving sufficient space between them to create uniform pore distribution without melting part or all of the disks into a uniform mass. This was a delicate process known as "sintering." Flawed electrodes shortened the useful life of a fuel cell.

[111] Crawley to Kenneth Rapp, 12 February 1958, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.280.

The successful demonstration of a six-kilowatt Bacon hydrogen fuel cell powering an electric welder and fork-lift truck in front of assembled visitors at Cambridge in late August 1959 was the zenith of the NRDC's involvement in fuel cell technology. In some ways, however, the event was bittersweet. As reported in the *Manchester Guardian Weekly*, the fact the Bacon cell would most likely find its first application in an American spacecraft rather than more prosaic roles in the land of its creation led to ill feeling among a number of guests and accusations that the program represented a failure of British "technological imagination."[114] The question of how the NRDC should proceed now that Pratt & Whitney had licensed the Bacon cell was uncertain. The status of the program at Marshall's was in doubt owing to the technology's reliance on pure hydrogen, the same reason the cell had been made a technological orphan. The NRDC had been no more successful than the ERA in seeking a British industrial sponsor for the technology and it was unclear precisely how the "national interest" had been served in developing and then licensing the technology to American companies heavily involved in military-industrial activities.

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[112] J.C. Frost, "Bacon Project," Notes from meeting at Marshall's Flying School, 10 June 1959, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.284.

[113] J.N. Haresnape, E.A. Shipley, G.H. Townend and K.E.V. Willis, "Energy Conversion Limited: Report of the Technical Working Party," January 1962, Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.774, 12.

The demonstration of the Bacon cell nevertheless caused an international stir, helping to raise the global profile of fuel cell technology and whetting appetites for a hydrocarbon variant. In September of 1959, Bacon was one of nine speakers featured at the world's first global conference on fuel cells staged by the American Chemical Society in Atlantic City, New Jersey. In the ensuing panel discussion, nothing was said of the economics of hydrogen. Instead, the audience expressed considerable interest in the future of carbonaceous fuel cell fuels and the role petroleum, chemical and coal companies would play in supplying them.[115]

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[114] "U.S. Interest in Fuel Cell," *Manchester Guardian Weekly*, 27 August 1959, p.4. The NRDC reported that it and the ERA had spent a total of £100,000 in developing the Bacon cell. This was equivalent to about £1.53 million in 2007.

[115] *Fuel Cells: A Symposium Held by the Gas and Fuel Division of the American Chemical Society at the 136th National Meeting in Atlantic City*, ed. G.J. Young (New York: Reinhold Publishing Corporation, 1960), 150-152. 150. In the introduction of the published collection of conference proceedings, General Electric's H.A. Liebhafsky and D.L. Douglas authoritatively defined a fuel cell as an electrochemical device that converted the chemical energy of a conventional or hydrocarbon fuel directly into useful DC energy (1). During the Army's Signal Laboratory Power Sources Conference in the spring, Army researcher Herbert Hunger similarly held that the fuel cell, or "continually-fed battery," as he termed it, would ultimately use carbonaceous fuels. These would be used either directly, through injection into the fuel cell electrolyte, or indirectly, by converting a hydrocarbon into a hydrogen-rich gas; Hunger, "Introductions, Concepts, and Survey," in *Proceedings: Thirteenth Annual Power Sources Conference, 28-30 April 1959* (Fort Monmouth, NJ: Power Sources Conference Committee, 1959), 105.

While fuel cell researchers almost unanimously lauded the Bacon cell as the technological standard, American industry could find no more use for it than British industry. Yet it set the benchmark for fuel cell performance. Shell was exploring an acid fuel cell it hoped would be as powerful as the Bacon cell.[116] As early as the spring of 1956, the period when the NRDC and ERA first entered into negotiations with the Americans, some researchers in the U.S. coal industry noted that while the Bacon cell was the outstanding example of a fuel cell operating between 200°C-500°C, "serious" fuel cells were "primary" power sources, and thus had to be capable of accepting carbonaceous fuels.[117]

By fall of 1959, the NRDC was looking for ways to withdraw from the project. Its 1960 program for Marshall's of Cambridge was extremely ambitious. Among other things, the NRDC called for development of an electrolyzer and an electrode capable of using hydrocarbons, as well as studying non-electrolytic means of hydrogen production.[118] As Marshall's fuel cell chief J.C. Frost noted, each goal represented a considerable effort in and of itself, work the engineering firm had neither the expertise nor the budget to undertake.[119] In calling for the conversion of the Bacon cell into a hydrocarbon device, the NRDC was in essence terminating the project. Its administrators began to cast about for other fuel cell technologies capable of using cheap commercial fuels, particularly a design using a molten carbonate electrolyte. Like all fuel cells, this one had offsetting pros and cons. Operating at temperatures as high as 700°C, the molten carbonate operating system was extremely corrosive and imposed thermal expansion on the fuel cell structure itself during start-up, with major implications for durability.

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[116] K.R. Williams to Bacon, 24 November 1959, Bacon TS, Section G, Correspondence, Fuel Cell Correspondence, G.122.

[117] E. Gorin and H.L. Recht, "Fuel Cells," in *Proceedings: Tenth Annual Battery Research and Development Conference, 23 May 1956* (Fort Monmouth, NJ: Battery Conference Committee, 1956), 54.

[118] H.J. Crawley, "Suggested Program for 1960," 6 October 1959, Bacon TS, Section B, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.318.

[119] J.C. Frost to H.C. Crawley, 9 October 1959, Bacon TS, B.318. Bacon appears to have been skeptical of the new direction of research. In his copy of the NRDC's suggested program, he penciled in a question mark next to the directive to examine "the possibility of catalytic hydrogen electrode in order to use hydrocarbon fuel."

By the late 1950s, this technology was still in a primitive state of development but, in theory, could tolerate carbonaceous fuels far better than acidic and basic designs. Consequently, it attracted the attention of the NRDC. By 1960, the corporation had become increasingly interested in H.H. Chambers' work on molten carbonate systems at the Sondes Place laboratory in London. Initially begun under a Ministry of Power contract, the project already had powerful backers in Shell and the Central Electricity Authority, which had refused Bacon aid in 1956. The NRDC moved to end work on the Bacon cell and build its fuel cell effort around molten carbonate technology, acquiring the Chambers patent, which was included in the Leesona-Moos licensing agreement in 1960.[120] In October 1961, the NRDC entered into a cooperative arrangement known as Energy Conversion Limited (ECL) with British Petroleum, British Ropes and the Guest, Keen & Nettlefolds Group (GKN).[121] Leesona, Pratt & Whitney and Energy Conversion Limited continued to have a complex licensing and information-sharing arrangement on the Bacon and Chambers patents that lasted into the 1970s. However, the molten carbonate system proved extremely difficult to make practical and Leesona and Pratt & Whitney focused their efforts in hydrocarbon fuel cells on designs using acidic electrolytes after the mid-1960s. In Britain, the Bacon cell passed into the pages of history. The NRDC ended its support in January 1961 and the program was dismantled. This marked the end of Bacon's career as a researcher and engineer and his contributions to science and technology. He remained active as an ECL technical consultant, an independent lobbyist and the elder statesperson of fuel cell technology.

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[120] Haresnape, Shipley, Townend and Willis, "Report of the Technical Working Party," January 1962, 12.

[121] John Maddox, "British Firm to Develop New Source of Power: A Future for the Fuel Cell," *The Guardian*, 30 October 1961.

In some ways, the Bacon cell story was an improbable chapter in the history of technology. Almost from the beginning, Bacon and his sponsors had understood that the hydrogen fuel cell was simply the energy conversion component of a larger energy production, storage and generation system. His expansive technological vision was no secret to the ERA and NRDC. By 1956, Bacon saw his fuel cell as the basis for a new energy and transportation order, one in which huge electrolyzers drawing off-peak electrical power would produce the hydrogen that would reduce Britain's dependence on imported oil.[122] But Bacon's patrons would fund only his fuel cell and he had always acquiesced, believing that the technical problems relating to fuel supply and storage could be solved elsewhere. In a 1957 letter to National Carbide's Karl Kordesch, Bacon admitted that the weight of existing hydrogen storage technology presented a "serious limitation" to his fuel cell. On the other hand, he noted, history taught that solutions were often developed for technological obstacles previously thought insuperable. After all, had not the problem of storing liquid oxygen been resolved?[123] This faith in the historical progress of technology, a constant theme in Bacon's correspondence, became a staple of his lectures and addresses during his later years.[124] It would also gird successive fuel cell research and development communities over the next 40 years as they struggled to bring the technology to market.

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[122] Bacon to Kordesch, 19 November 1956, Bacon TS, Section G, Correspondence, Fuel Cell Correspondence, G.120.

[123] Bacon to Kordesch, 23 February 1957, Bacon TS, G.120.

In contrast to Bacon's sweeping vision, Kordesch was willing to consider smaller applications for alkaline hydrogen fuel cells, noting the difficulties that arose when fuel weight exceeded cell weight in larger applications.[125] Bacon's aspirations resembled those of the early proponents of the battery electric automobile who sought "electric multifunctionalism." In the early 1900s, inventors and their sponsors aimed to compete with internal combustion vehicles in every application and on every level of cost, convenience and comfort. After the Second World War, the sponsors of electric vehicles abandoned such hopes, focusing on niche applications, particularly industrial factory trucks.[126]

Bacon's patrons indulged his dreams for almost a decade and a half. Impressed by his laboratory accomplishments, intrigued by the possibilities of electrochemical energy conversion, above all the hope that the device could one day be made to run on hydrocarbons, they ultimately rejected his all-encompassing vision for the hydrogen fuel cell. Together, they produced the Bacon cell, the most advanced fuel cell in the world in 1960, with by far the highest current density. But the only options left for development, as Bacon knew, were in niche roles where the high cost of using pure hydrogen and oxygen could be easily accommodated. As we shall see in chapter four, only the U.S. military aerospace complex was prepared to furnish the fuel production and storage technologies necessary for the Bacon cell to flourish.

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[124] For instance, see Bacon, "The Fuel Cell: Some Thoughts and Recollections," *Journal of the Electrochemical Society* 126, no. 1 (January 1979); and Bacon and Fry, "Review Lecture: The Development and Practical Application of Fuel Cells," *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences* 334, no. 1599 (25 September 1973).

[125] Kordesch to Bacon, 28 January 1957, Bacon TS, Section B, Research and Development, Correspondence, Fuel Cell Correspondence, G.120.

[126] Gijs Mom, *The Electric Vehicle: Technology and Expectations in the Automobile Age* (Baltimore: The Johns Hopkins University Press, 2004), 300.

The technology also important ideological effects. It served as an exemplar of progress, informing grand dreams of a new energy order on both sides of the Atlantic and playing a major role in triggering the fuel cell boom of the 1960s.[127] In the introduction to the published proceedings of the American Chemical Society's second international conference on fuel cells of 1961, Anthony M. Moos, the co-founder of the company that brought the Bacon cell to the United States, noted how fuel cell technology programs had proliferated since the "dedicated pioneer" Bacon had worked under the ERA's sponsorship. Quoting from the same 1875 issue of the *Congressional Record* cited by the Harvard Business School graduates in their 1960 survey, Moos claimed the world stood on the brink of a new energy revolution. This depended on the ability of fuel cells to use "cheap and readily available fuels" like natural gas and propane at moderate temperatures.[128] Such a goal would form the main thrust of the U.S. Defense Department's program of fuel cell research and development in the 1960s.

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[127] Though development on the Bacon cell ended in Britain in 1960, work on other classes of fuel cell, particularly the molten carbonate type, continued. For Labour Prime Minister Harold Wilson, fuel cell technology, along with the hovercraft and the Atlas computer, were politically important. He cited this high technology triptych several times in 1963 and 1964 as evidence of the vitality of British innovation; see David Edgerton, *Warfare State: Britain, 1920-1970* (Cambridge: Cambridge University Press, 2006), 218.

[128] Anthony M. Moos, "Introduction," in *Fuel Cells Volume II: A Symposium Held by the Divisions of Fuel Chemistry of the American Chemical Society at the 140th National Meeting in Chicago*, ed. G.J Young (New York: Reinhold Publishing Corporation, 1963), 1.

2 - Making the Army's Miracle Battery: The Advanced Research Projects Agency, Civilian Scientific Expertise and Military-Industrial Research and Development

The story of post-Second World War fuel cell development in the United States is inextricably linked to the emergence of the military industrial and aerospace complex. As the Cold War intensified in the early 1950s, developments in military technology created requirements for new power sources like the Bacon cell. In the wake of the bloody stalemate in Korea, President Dwight Eisenhower's "New Look" defense policy emphasized atomic and nuclear weapons, and the jet aircraft and rockets to deliver them, over conventional forces. An important aspect of this revolution in warfare was the application of transistors in radios, radars and computers, facilitating major advances in communications, surveillance and weapons guidance and control. But transistorized technology had unprecedented power source needs. Amidst the techno-social upheaval of the missile age, researchers and planners within the American military establishment saw the fuel cell as a promising solution.

Among the various armed services, interest was strongest in the Army, which had studied a number of fuel cell concepts since the early 1950s. The character of this armed service's fuel cell program after 1960 was determined largely by the Advanced Research Projects Agency (ARPA), an institution founded as the nation's first space agency and later the Defense Department's premier sponsor of applied research. Along with NASA, ARPA played a critical role in developing expectations for fuel cell technology. It helped shift the emphasis of the Army's fuel cell program from specialized hydrogen-fueled devices to hydrocarbon-consuming technology intended for a wide variety of applications. To this end, ARPA administered Project Lorraine, the Defense Department's program of applied research in power sources, of which the hydrocarbon fuel cell was the most important single element. This joint industry-military effort also formed the basis of the first commercial terrestrial fuel cell program in the United States.

In exploring ARPA's Project Lorraine from its inception in 1960 to its termination in 1965, this chapter will examine how Cold War political pressures informed notions of the efficacy of terrestrial hydrocarbon fuel cell technology within the U.S. Department of Defence. I will also address the consequences of military-industrial patronage for commercial fuel cell technology in the 1960s. As Callon has noted in the French context, and as we have observed in the case of the Bacon cell, the perception of fuel cells as a revolutionary "high" technology helped make them an object of desire and bargaining chip in struggles for power and influence among science and technology communities. These dynamics played as much of a role as technical merit and the requirements of end-users in shaping the resultant artifacts.

For ARPA, fuel cell research and development was an important way to justify its existence, especially after it was forced to relinquish its space responsibilities to NASA in 1959. As ARPA struggled to carve out a role for itself in the rapidly changing post-Sputnik defense science and technology establishment, its objectives and expectations in the hydrocarbon fuel cell program were conditioned by pressure to produce quick returns for investment in basic research. In this, ARPA was heavily influenced by the Institute for Defense Analyses, a civilian think tank with connections throughout the military-industrial complex and its own vision of a fuel cell-based energy and transportation order.

Institutionalizing Interdisciplinarity: Fuel Cells and the Revolution in Materials Science and Engineering

Virtually nothing has been written of the roles of the Department of Defense and ARPA in developing terrestrial fuel cells during the 1960s. This is remarkable, considering that the Pentagon was the second most important sponsor of fuel cell technology after NASA in this period, spending at least $10 million between 1960 and 1970. While A.J. Appleby and F.R. Foulkes devoted some space in *Fuel Cell Handbook* to military fuel cells, this focused exclusively on the Army's efforts to develop prototype hardware, which began in 1965.[1] Left unmentioned was Project Lorraine, ARPA's program of fuel cell research between 1960 and 1965. Conceived as the "basic" phase of research preceding the Army's "applied" program, Project Lorraine played a crucial role in shaping expectations and the kinds of technologies eventually selected by the Army for further development.

The Pentagon's involvement in fuel cell technology began in a period when the structure of the U.S. defense research and development establishment was in flux. Drawing on their experience of the Second World War, government administrators, academic researchers and corporate managers acknowledged the indispensability of science in advanced weapons systems and entered into the close partnership known as the "golden triangle."[2] But the "golden triangle" did not spring forth fully formed in the immediate aftermath of the Second World War. The institutionalization of interdisciplinarity in complex weapons programs, and the resultant diffusion of administrative responsibility, raised a host of problems relating to jurisdiction, accountability and authority that greatly complicated the management of science-based weapons programs. The military's interest in fuel cells was stimulated as much by intra and extramural politics as by objective requirements for an advanced power source. These political battles had a crucial effect on ARPA's administration of the Department of Defense's power conversion technology program and on the conduct of work at the laboratory level.

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[1] A.J. Appleby, "Fuel Cells for Tactical Battlefield Power," *IEEE AES Systems Magazine* (December 1991): 49-55; A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), 151.

[2] Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993), 2.

The basic question facing defense planners as the Cold War escalated was how best to yield technological innovation from science. Michael Aaron Dennis has observed that university science programs engaged in arms research during the Second World War were sustained above all by "production," a steady output of advanced weaponry and the dissemination of knowledge relating to the production of hardware.[3] In the postwar period, "production" remained the key preoccupation of government, industry and university planners and the overriding concern not only of university but industrial laboratories engaged in defense-related work. For all these groups, the success of the wartime arms programs pointed the way to the future. Much of this work had been coordinated by the Office of Scientific Research and Development (OSRD), a temporary body created by executive order at the recommendation of Vannevar Bush, the former dean of engineering at the Massachusetts Institute of Technology. Independent of the military and with no facilities of its own, the OSRD contracted at academic and industrial laboratories. For the civilian engineers and scientists who had been instrumental in its creation, this was the ideal institutional model for post-war research and development.[4] Fruitful wartime collaboration between the government, university-based theorists and experimentalists and industry reinforced widely-held beliefs of the efficacy of the linear model, championed by Bush above all, in which basic science led directly and rapidly to new hardware.[5]

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[3] Michael Aaron Dennis, "'Our First Line of Defense:' Two University Laboratories in the Postwar American State," *Isis* 85 (1994): 429.

Configuring the "golden triangle" in the postwar period, however, proved far more difficult than linear models indicated. Beyond the general agreement that science could be extremely "productive," opinion was deeply fractured among the various interest groups over how much autonomy science, and scientists, would have in relation to the White House, the military and industry. Bush's linear formula implied that in order to be "productive," theoretical modeling and engineering were best practiced within separate, dedicated establishments, a view current in the late 1940s and 1950s.[6] Though Bush's vision of an autonomous institutional home for basic scientific research was ultimately defeated by President Harry Truman and his Congressional allies, the military moved in the interim to assert authority over weapons research and development policy assumed by the OSRD during the war. The result was precisely the kind of institutions of basic science that many scientists had desired. The Office of Naval Research and the Atomic Energy Commission provided unparalleled resources and authority to scientists to conduct research.

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[4] Daniel J. Kevles, "K1S2: Korea, Science, and the State," in *Big Science: The Growth of Large-Scale Research*, eds. Peter Galison and Bruce Hevly (Stanford, CA: Stanford University Press, 1992), 313.

[5] John Kenly Smith, Jr., "The Scientific Tradition in American Industrial Research," *Technology and Culture* 31: 1 (January 1990): 128.

[6] William O. Baker, "Advances in Materials Research and Development," in *Advancing Materials Research*, eds. Peter A. Psaras and H. Dale Langford (Washington, D.C.: National Academy Press, 1987), 20.

The military viewed the mobilization of civilian scientists and defense research policy experts as a mixed blessing. While the power to control foreign policy ultimately lay with the federal government, scientists were nevertheless well placed to shape perceptions of the capabilities of science and technology in meeting its Cold War objectives. As Daniel Greenberg has noted, civilian scientific advisors identified issues, framed questions and produced data.[7] Civilian researchers in a score of weapons laboratories competed to promote ideas to the Department of Defense, telling Washington what it needed to win the Cold War, not the other way around.[8] Paradoxically, the military establishment distrusted civilian advisors and worked to ensure its control over them, yet increasingly relied on their expertise as weapons were made more powerful and complex. After the Second World War, in the face of considerable resistance from the armed services, Bush and his influential acolyte Lloyd Berkner worked to institutionalize civilian scientific expertise in military planning circles, raising a series of civilian-military advisory panels that coordinated the research and development of advanced weapons systems and national security policy. The Advanced Research Projects Agency and its fuel cell policy had origins in these political maneuvers.

The first of these advisory panels, the Joint Research and Development Board, was formed in 1946 and succeeded by the Research and Development Board. Prompted by Bush, Defense Secretary James Forrestal proposed empowering the board's scientists to shape the future conduct of warfare and military missions. When the service chiefs objected, Berkner was asked to broker a solution. He recommended the formation of the Weapons System Evaluation Group (WSEG), an organization with an advisory role only.[9] By the mid-1950s, military and civilian planners were looking to universities as a key reservoir of expertise. The WSEG was then the top advisory panel in the military. Attached directly to the Joint Chiefs of Staff and employing a mix of civilians and military specialists, the WSEG engaged in operations research and systems analysis, assessing new weapons technologies for effectiveness and suggesting ways of employing them in combat.[10] One result of the efforts of military commanders to bolster the group's advisory power was the Institute for Defense Analyses (IDA), a private university consortium.[11] Formed by the Massachusetts Institute of Technology in 1954 at the request of the secretary of defense and the chairman of the Joint Chiefs of Staff, the IDA supplied systems analysis to the military.[12] Where the WSEG was concerned, the institute recruited civilian scientists and managed their activities within the group.

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[7] Daniel S. Greenberg, *The Politics of Pure Science*, new ed. (Chicago: University of Chicago Press, 1999), 168.
[8] Daniel Kevles, "R&D and the Arms Race: An Analytical Look," in *Science, Technology and the Military* vol. 2, eds. Everett Mendelsohn, Merritt Roe Smith and Peter Weingart (Dordrecht, Netherlands: Kluwer Academic Publishers, 1988), 472-476.

However, the military's support of university research remained on an ad hoc basis until after the launch of *Sputnik* in October 1957. Stung by the Soviet triumph, the Department of Defense embarked on major internal restructuring designed to systematically mobilize the nation's civilian scientific resources. One of Defense Secretary Neil McElroy's first acts was to establish ARPA by executive order. Inaugurated in January 1958, the agency became active in February and March. The Defense Reorganization Act of 1958, passed in September, greatly the enlarged the role of civilian scientific advice in the military and resulted in the creation of the Office of the Director of Defense Research and Engineering (DDR&E). This was a civilian post equal in rank with the departments of the military services and responsible for ARPA and all military research projects. Together, these bureaus formed the principal organs of military basic research.[13] At the request of McElroy, the IDA expanded its role, establishing a special division to supply ARPA with systems analysis.[14] This institute played a crucial role in shaping the military's expectations of fuel cells and the conduct of ARPA's research and development programs.

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[9] Allan A. Needell, *Science, Cold War and the American State: Lloyd V. Berkner and the Balance of Professional Ideals* (Amsterdam: Harwood Academic, 2000), 119-121.

[10] Herbert F. York, *Making Weapons, Talking Peace: A Physicist's Odyssey from Hiroshima to Geneva* (New York: Basic Books, 1987), 141. Developed during the Second World War, operations research was a kind of scientific management used by planners to assess the performance of existing weapons systems in wartime and improve their efficacy. Systems analysis was developed in the Cold War period and involved the use of theoretical models in an effort to predict the performance of advanced nuclear weapons systems in the event of war.

[11] Silvan S. Schweber, "The Mutual Embrace of Science and the Military: ONR and the Growth of Physics in the United States After World War II," in *Science, Technology and the Military* vol. 1, eds. Everett Mendelsohn, Merritt Roe Smith and Peter Weingart (Dordrecht, Netherlands: Kluwer Academic Publishers, 1988), 34.

[12] Alexander Kossiakoff, "Conception of New Defense Systems and the Role of Government R&D Centers," in *The Genesis of New Weapons: Decision-Making for Military R&D*, eds. Franklin A. Long and Judith Reppy (New York: Pergamon Press, 1980), 65.

From its inception, ARPA's involvement in fuel cells and its organization and conduct of Project Lorraine was bound up in the struggle between the various branches of the military for control of space technology and the institutional and educational reforms that accompanied efforts to develop it. Alex Roland has claimed that ARPA originated as an "institutional barrier" erected by the Department of Defense as a way of tempering the fierce competition and redundancy that resulted after the armed services accelerated existing missile and space programs and lobbied for new ones following the launch of Sputnik.[15] This was an important consideration in McElroy's decision. However, the agency's managers quickly developed appetites of their own and sought to stake out turf in the defense research community and control their share of science and technology development. Consequently, as we shall see, ARPA played a much more active role as a sponsor and monitor of advanced science and technology programs in its early days than Roland indicates. Herbert York, ARPA's first chief scientist and later the first Director of Defense Research and Engineering, noted that McElroy set up the agency both as a means to allow the Office of the Secretary of Defense to reassert control over weapons development policy and take charge of those military technology projects in very early stages of development that were being retarded by inter-service rivalry. As a civilian-led quasi-military bureau, ARPA would also sponsor radical new concepts that were being ignored altogether and did not clearly fall under the purview of any one armed service.[16] With such a mandate, ARPA's managers developed expansive interpretations of their mandate. The agency's first director, Roy W. Johnson, a former General Electric executive vice-president, envisioned the bureau as the national space agency, dedicated above all to the defense mission. Along with many IDA personnel, Johnson fought hard to manage large defense-related space technology projects, above all launch vehicles. This pitted ARPA not only against the armed services but also the White House. Backed by the President's Science Advisory Committee (PSAC), Eisenhower was determined to vest American space activities in a civilian institution.[17] In the meantime, ARPA, with a staff of little more than 100, had by 1959 assumed administrative responsibility for Army and Air Force booster rockets, military payloads, ballistic missile defense and miscellaneous space technologies including energy conversion devices. Fuel cells fell under the rubric of the latter, though they were not then a high priority among these.[18]

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[13] David Dickson, *The New Politics of Science* (New York: Pantheon Books, 1984), 119-120.
[14] "About IDA," http://www.ida.org/IDAnew/Welcome/history.html, accessed 20 January 2006.
[15] Alex Roland, "Science, Technology and War," *Technology and Culture* 36, no. 2 Supplement (April 1995): S94.

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[16] York, *Making Weapons, Talking Peace*, 136-138.

[17] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974* (Washington, D.C: ARPA, 1975), II-35, III-24-III-39; York, *Making Weapons, Talking Peace*, 174-175.

Nevertheless, in a period when U.S. military and industry researchers, like their British counterparts, struggled to develop suitable fuel cell applications, ARPA played an important function in highlighting aerospace as one of the first practical uses of the technology. The agency figured prominently in the annual power source symposium sponsored by the Army Signal Corps, focusing on space as the overarching theme. Delivering the 1959 conference's keynote address, ARPA's representative had mentioned the "well-developed" hydrogen-oxygen cell - an oblique reference to the Bacon cell - as a suitable candidate for space missions of medium duration limited by the weight of fuel owing to the technology's comparatively high power output.[19]

Fuel cells took on greater importance within ARPA following the creation National Aeronautics and Space Administration in the fall of 1958. With U.S. space policy now under civilian control, ARPA became redundant. In the summer of 1959, York, then Director of Defense Research and Engineering, moved to divest it of its space projects, restricting it to "the field which is defined by its name," in the words of George Kistiakowsky, the president's special assistant for science and technology. Feeling that the current organization of research and development allowed the Air Force to draft "fantastic requirements" it then expected ARPA to execute, York wanted to turn purely military space programs over to this armed service, forcing it to pay for its own rocket research and development. This, he hoped, would cool its ardour for such technologies.[20]

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[18] Nathan W. Snyder, "IDA IM 155: Research in Advanced Energy Conversion," 4 January 1960, 1958-1966 Official Correspondence Files-Materials Sciences Office, Advanced Research Projects Agency, accession number 68-A-2658, RG 330, Box 4, Project Lorraine-Energy Conversion, 24-26, National Archives and Records Administration II, College Park, MD. ARPA funded work on thermionic, thermoelectric, and photoelectric devices in addition to fuel cells; the Army's Signal Corps managed the photoelectrical and electrochemical projects while the Office of Naval Research (ONR) managed thermionic contracts and shared responsibility for thermoelectric projects with the Bureau of Ships (BuS). Of the four technologies included in ARPA's Fiscal Year 1959 operations (fall, 1958-spring, 1959), fuel cells placed third in funding under the rubric of electrochemistry: photoelectricity ($566,450), thermoelectricity ($285,000), electrochemistry ($117,610), thermionic ($100,000).

[19] Snyder, "Space Power," in *Proceedings: Thirteenth Annual Power Sources Conference, 28-30 April 1959* (Fort Monmouth, NJ: Power Sources Conference Committee, 1959), 9.

York also wanted to transfer Wernher von Braun's Army rocket team and its Saturn IB booster from ARPA to NASA management, reasoning that there was little military justification for such a large rocket. Johnson and many IDA planners objected fiercely. George P. Sutton, the agency's chief scientist, was concerned about the "disastrous" effect such a transfer would have on its staff. Sutton did not mind relinquishing the large space projects so much as the loss of the "space research."[21] Nevertheless, York relieved ARPA of its space responsibilities in the fall of 1959, a decision he regarded as the most important he made while working at the Pentagon.

With ARPA's future unclear, York and its managers acted to reinvent it. One of these efforts involved salvaging the energy conversion projects including fuel cells that ARPA had supported for the space program and making them one of the agency's "principal efforts." In fact, this plan was the brainchild of IDA officials. In the atmosphere of national crisis provoked by Sputnik, the two bureaucracies developed an unusually intimate relationship. In the haste to set up a space agency, the White House, Congress and the Department of Defense arranged for the IDA to take responsibility for organizing and staffing ARPA and provided it sweeping powers to do so. The institute was given the contract to hire all of ARPA's personnel and then assign them to posts within the Pentagon as directed by ARPA's management. Both ARPA and IDA staff were allowed to approach private companies that were under contract to the Department of Defense and recruit their staff to work for them for periods of one to two years during which they would receive compensation only from the IDA. In short, industry researchers were paid to advise ARPA on the disbursement of contracts to industry. The opportunities for conflict of interest were considerable. As York noted, such an arrangement was normally considered improper, even illegal, but it was deemed expedient in a time of national emergency.[22] Consequently, IDA personnel, largely recruited from industry, constituted the core of the ARPA bureaucracy for the first few years of the new agency's existence, moving easily between the two bureaus and exercising great influence in planning the initial projects and selecting contractors.[23] As ARPA's financial manager Lawrence P. Gise noted, IDA staffers within the agency were biased towards technology programs, earning ARPA a dubious reputation in certain scientific circles for a time.[24]

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[20] George B. Kistiakowsky, *A Scientist at the White House: The Private Diary of President Eisenhower's Special Assistant for Science and Technology* (Cambridge, MA: Harvard University Press, 1976), 31, 57.

[21] Kistiakowsky, *A Scientist at the White House*, 91, 102.

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[22] York, *Making Weapons, Talking Peace*, 141.

[23] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974*, IV-13-IV-15; James R. Killian, Jr., *Sputnik, Scientists and Eisenhower: A Memoir of the First Special Assistant to the President for Science and Technology*, 129; York, *Making Weapons, Talking Peace*, 141. Though York had been appointed as ARPA's chief scientist on the recommendation of James Killian, head of the President's Scientific Advisory Committee, he had actually been hired through the IDA; Other major figures in defense policy such as George W. Rathjens and Jack Ruina also worked at both ARPA and the IDA.

[24] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974*, IV-14.

In this tumultuous transitional period, the Department of Defense's fuel cell program was shaped by the conflicting interests of these two groups of managers as each worked to foster a new institutional identity for ARPA following the loss of the space technology mission. Aware that ARPA engendered too much hostility among the armed services and had too small a budget to effectively guide any advanced technology program from research through development and production, Johnson and his aides recommended to Defense Secretary McElroy in September 1959 that ARPA be remade as a sponsor of basic research. This became the agency's new role after 1960.[25]

However, the agency's transition from a manager of technology programs to a manager of basic research programs would generate great confusion among IDA and ARPA planners. As ARPA's priorities and expectations changed, there were internal disagreements not simply over how work on fuel cells should best be conducted, monitored and assessed but on the very doctrinal justification for the effort. As the official ARPA history notes, fuel cells were part of a collection of energy conversion technologies retained from the agency's space technology days. But ARPA's energy conversion program was also strongly connected with its program in materials sciences. Begun in 1959, this long-term effort in basic research to synthesize new durable materials for use in energy conversion and space technologies enjoyed wide support throughout the defense research establishment.[26] More will be said on the relationship between ARPA's energy conversion and materials programs momentarily. The key point to note at this juncture is that fuel cells and other energy conversion devices were out of place in ARPA's new mission: even as the agency worked to establish itself as an administrator of open-ended basic research, it retained control of a technology program with important advanced material needs requiring basic research.

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[25] Ibid., III-2, III-70-III-76. ARPA's budget peaked at $520 million in Fiscal Year 1959 before declining to around $250 million per annum during the 1960s.

[26] Robert L. Sproull, "Materials Research Laboratories: The Early Years," in *Advancing Materials Research*, eds. Peter A. Psaras and H. Dale Langford (Washington, D.C.: National Academy Press, 1987), 27-29.

In seeking a philosophical justification for ARPA's energy conversion program, the IDA attempted to reconcile the "scientific" with the "technological." This was developed by Nathan W. Snyder, the power systems specialist who had delivered the presentation at the Army Signal Laboratory power sources conference in the spring of 1959 on behalf of ARPA. Now working for the IDA, he recommended ARPA preserve its power source programs and prescribed a linear blueprint for managing fuel cell research and development. This outlined new applications and justifications for the continuation of research and development, which had formerly been restricted to fundamental studies of materials and components. Snyder held that the knowledge obtained in the course of space power research was transferable to terrestrial use, claiming that space vehicles and ground vehicles had similar requirements. Indeed, he stated, much of the work in the space power program was of equal or greater value in terrestrial or marine applications.[27]

Following ARPA's new policy line, Snyder argued that there was no basic research program in energy conversion technology serving all the military services. The work of the Department of Defense in this field, he claimed, was biased towards hardware development. Scientists eager to undertake advanced basic research in energy conversion could not because of government neglect. If this state of affairs continued, Snyder noted, scientists would be relegated to improving existing systems rather than making technological breakthroughs. Because the power source requirements of the individual armed services were similar, he said, ARPA could exploit space power research to develop "fundamental" knowledge of value to all. Snyder recommended the agency's energy conversion program have a close relationship with its materials sciences program, its primary effort in basic science. The individual armed services would then fund the expensive demonstrations of energy conversion hardware.[28]

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[27] Snyder, "IDA IM 155: Research in Advanced Energy Conversion," Box 4, Project Lorraine-Energy Conversion, 1, National Archives and Records Administration II, College Park, MD.

In short, Snyder proposed to completely reorganize the Department of Defense's power source research and development program by repositioning ARPA as the all-service body responsible for administering basic research. True to its credo, ARPA would be supporting advanced programs in areas that were being neglected by the defense research establishment, not existing hardware programs. To reinforce his point, Snyder warned that a price in national security would be exacted if science was not adequately supported, a tactic often used by scientists, especially physicists, in leveraging political advantage during the Cold War.[29] Snyder invoked linear logic to make this argument. Certain institutions like ARPA and its industrial contractors, he claimed, were better adapted to promulgating basic research. Others, the armed services and their private contractors, were best suited for applying this knowledge. For this scheme to work, one had to assume that there was no engineering involved in the basic phase of fuel cell research and that fundamental research did not take place during the engineering phase.

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[28] Ibid., 4. In Fiscal Year 1959, ARPA spent $2.34 million on space power research.
[29] Greenberg, *The Politics of Pure Science*, 215-218.

Snyder's paper proved influential. Along with another IDA report, it informed the decision of the Office of the Director of Defense Research and Engineering to initiate Project Lorraine.[30] A conference held on 24 October 1960 between Snyder and DDR&E and ARPA officials confirmed that work would concentrate on "physical principles."[31] The agency had become the home of last resort for fuel cell technology in a way that recalled the experience of the Electrical Research Association and the National Research Development Corporation in Britain. ARPA management accepted Snyder and the IDA's assessment of the Department of Defense's energy conversion program, above all the claims of bias towards hardware at the expense of basic research and the idea that different power source applications were essentially interchangeable.[32]

These assumptions were reflected in the organization of the portion of Project Lorraine concerned with electrochemical energy conversion, which had among its goals the development of a hydrocarbon fuel cell. They were also accepted by the Army, the armed service most interested in this technology. But the notion of a universal energy converter was attractive in other quarters of government, as well as industry. While NASA would develop very specific and limited goals for fuel cells, the idea that the space program would "spin-off" civilian commercial applications appealed to administration planners under increasing pressure to justify their expenditures as the 1960s progressed. The revolving-door nature of the defense science advisory apparatus and the fact that such advice was inextricably bound up in parochial bureaucratic objectives meant that a truly independent assessment of fuel cell technology was very difficult to obtain. As IDA and Army researchers informed ARPA's understanding of fuel cells, which in turn reinforced their own views, a positive feedback loop was established in which *a priori* notions of the technology were bolstered and transmitted throughout the defense establishment.

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[30] Memorandum, "Project Lorraine Summary," undated, Box 4, Project Lorraine-Energy Conversion, National Archives and Records Administration II, College Park, MD.
[31] Memorandum by Urner Liddel, 24 October 1960, Box 4, Project Lorraine-Energy Conversion.
[32] Memorandum, "DD Form 613: ARPA Program Statement: Advanced Energy Conversion Research," 19 August 1960, Box 4, Project Lorraine-Energy Conversion, 1-2.

Accounting for Research and Development: Linear Project Management

The official history of ARPA rightly observes that the circumstances of the creation of Project Lorraine reflected agency policy in this transitional period. The episode, it claims, demonstrated the dominant role played by the IDA in setting ARPA's priorities, notably the all-service justification for basic science and the association of energy conversion with the politically popular materials research program.[33] What the history does not consider are the problems an agency dedicated to basic research faced in managing a hybrid "science" and "technology" program. One of the hallmark features of this period of institutional upheaval in U.S. golden triangle relations was the emergence of antithetical management philosophies that would crucially shape the conduct of ARPA's terrestrial fuel cell program. On the one hand, the managers of Project Lorraine subscribed to the broader trend within the Pentagon that favored the linear management of technology innovation. Glen R. Asner observes that during the 1950s, corporate defense contractors successfully lobbied to loosen government restrictions on reimbursing research expenses in weapons development programs. Prior to 1958, the U.S. military compensated corporate contractors only for research directly associated with the production of hardware. In the aftermath of *Sputnik*, the federal government agreed to reimburse first undirected "basic" research - research not readily identifiable with technology procurement programs - and then, under industry pressure, "applied" research - on the grounds that it was difficult in practice to distinguish between the two.

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[33] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974*, IV-39.

The result was the Department of Defense's Independent Research and Development program. In order to impose accountability and maintain managerial control of this massive expansion of undirected basic research, the Pentagon moved to strictly define each work practice, linking them in a sequential, linear process: "basic research" increased scientific knowledge, "applied research" expanded the potential of this knowledge and "development" involved the use of this knowledge to produce useful hardware. The Pentagon's requirement that contractors separately account for costs in each of these categories led many to structure their weapons development programs in discrete divisions responsible for research, development and manufacturing.[34] A similar process would occur in Project Lorraine.

Developing in parallel with linear-style management was interdisciplinary research and development, which implied reciprocal, non-sequential relations between science and engineering practices. This new mode of innovation originated in commercial industry and was becoming increasingly popular in defense research circles by the late 1950s. Leading planners in the federal government and the private sector had been impressed by the new technologies produced by industrial laboratories including the transistor, the solar cell and new polymers. They hoped to adapt the structure of the industrial laboratory, which combined science and engineering under one broad institutional umbrella, in developing materials suitable for the rigors of missile and space flight. The result was a discipline known as "materials science," a combination of physics, chemistry, mathematics and engineering. In the words of William O. Baker, vice-president of Bell Laboratories, a member of the President's Science Advisory Committee and a major promoter of the concept, materials sciences was the most promising way to convert "scientific discovery" into "technologic innovation and commercial and public production."[35]

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[34] Glen R. Asner, "The Linear Model, the U.S. Department of Defense and the Golden Age of Industrial Research," in *The Science-Industry Nexus: History, Policy, Implications*, eds. Karl Grandin, Nina Wormbs and Sven Widmalm (Sagamore Beach, MA: Science History Publications/USA 2004), 3-12.

The notion of a materials sciences program quickly gathered broad support among federal agencies including the Atomic Energy Commission, the Office of Naval Research, the National Science Foundation, the National Academy of Sciences and the Department of Defence, as well as the White House. Federal science and technology officials believed that universities were the best venue for such a project, featuring both a ready-made interdisciplinary capability and the ability to reproduce a technoscientific workforce.[36] After divesting ARPA of its main space projects, York saw the agency as a suitable manager of the program. It would become the prime mover of what Stuart Leslie has termed the "materials revolution."[37] As the lead federal agency in the National Materials Program (NMP), ARPA sponsored the creation of so-called Interdisciplinary Laboratories (IDL, later renamed Materials Research Laboratories, or MRL) at leading U.S. universities between 1960 and 1972.

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[35] Baker, "Advances in Materials Research and Development," in *Advancing Materials Research*, eds. Peter A. Psaras and H. Dale Langford (Washington, D.C.: National Academy Press, 1987), 5-7.

[36] Robert L. Sproull, "Materials Research Laboratories: The Early Years," in *Advancing Materials Research*, 27-29.

[37] Leslie, *The Cold War and American Science*, 213.

The agency adopted a hands-off approach to management, drafting broad objectives and supplying university laboratories with general work orders relating to the investigation of the theoretical properties of materials. ARPA also provided university researchers with generous time to transform science into useful technology, writing four-year contracts on the grounds that these were much more productive than one-year contracts.[38]

The administrators of Project Lorraine blended these two conflicting management philosophies. Although separate from the IDL program, the largest part of ARPA's materials sciences program, energy conversion in some ways overlapped it. Both were administered by ARPA's Materials Sciences Office and both focused on the discovery of the basic physical principles of materials with a view to eventual practical application. Here, the similarities ended. University laboratories were weakly represented in Project Lorraine's "golden triangle," with most contracts going instead to industrial laboratories, particularly those of Esso and General Electric. This would spark debate within the Materials Sciences Office, leading to demands that more academic research should brought to be bear on the problem of fuel cell electrochemistry. Further, although Project Lorraine's objectives were originally as broad as those of the IDL program, the timeline for results was much tighter. The consensus within the defense research community was that the IDL was so vital for long-term innovation that it was unnecessary to link it with specific military requirements. As befitted a program of basic science, the IDL timeline was open-ended.[39] Conversely, the issue of direct military application was more pronounced in

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[38] Sproull, "Materials Research Laboratories: The Early Years," 32.

[39] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974*, V-46.

Project Lorraine because, unlike the IDL program, researchers were simultaneously developing advanced materials *and* integrating them into pieces of prototype hardware. The hybrid "science" and "technology" nature of the agency's energy conversion program, the negligible contribution of university laboratories and the dominant role of industrial laboratories helped feed expectations for a quick technological "payoff" among the various interest groups that did not exist in the IDL program.

At first, ARPA did not request proposals from prospective fuel cell contractors for specific tasks. Instead, scientists themselves were encouraged to select those research questions they deemed the most interesting. Consequently, the program was originally configured around unsolicited proposals relevant to Project Lorraine's general objectives.[40] Despite this flexibility, ARPA funded contracts only on an annual basis, with renewal contingent on performance reviews. This created a powerful incentive for scientists to explore the kinds of problems that generated immediate results. Thus guided by ARPA, managers of industrial research programs sought the path of least engineering resistance, demonstrating high current density on laboratory fuel cells using the most easily electro-oxidized fuels.

The ambiguous standards that identified procedures of basic research as successful were made more opaque by the complexity both of the technological objectives and the channels of communication through which ARPA monitored progress. Agency managers initially encouraged experiments on light hydrocarbons in the belief that they would provide valuable experience relevant to more chemically complex fuels that industry and the Army wanted to use including gasoline, kerosene-based jet fuels and diesel oil. These substances, however, behaved quite unlike the lighter hydrocarbons under conditions of electro-oxidation and proved exceedingly difficult to completely reduce to hydrogen. Over the course of the program, industrial contractors fed optimistic progress reports to the IDA, which were in turn passed on to ARPA managers, giving them the impression that the more difficult goal of using heavy hydrocarbons in fuel cells was in fact achievable. This fostered a questionable overall picture of progress, leading researchers to persist with certain lines of inquiry they might otherwise have abandoned.

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[40] "Project Lorraine Summary/Modified DD Form 613," fall 1960, Box 4, Project Lorraine-Energy Conversion, 1, National Archives and Records Administration II, College Park, MD.

What was more, ARPA's annual performance-based reviews and linear management hindered the work of the industrial laboratories. From the outset, ARPA managers stated that they would only fund research on basic "physical principles" and possibly "fundamental engineering principles," but would not administer hardware development. That was to be left to the Army's laboratories.[41] In practice, however, distinguishing between a search for "physical principles" and "fundamental engineering principles" was very difficult. As Robert Kargon, Stuart Leslie and Erica Schoenberger note, the conduct of advanced technology innovation in the golden triangle was non-linear, involving "frequent interaction and rapid feedback" among engineers, academic scientists and government administrators.[42] This also characterized the work of General Electric's fuel cell division as it began to accept the first Project Lorraine contracts. By then, the company already had several years of experience with fuel cells during which it had organized its energy conversion laboratories along conventional "basic" and "applied" lines. By 1961, however, these laboratories were becoming interdisciplinary, with the basic and applied research units acquiring techno-scientific characteristics.[43] Yet ARPA did not recognize this shift and continued to operate as if General Electric still had discrete basic and applied programs. Accordingly, ARPA linked the funding of the "applied" laboratory to progress made in the "basic" laboratory, greatly inhibiting the engineering research aspect of the program.

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[41] Memorandum by Urner Liddel, 24 October 1960, Box 4, Project Lorraine-Energy Conversion.
[42] Robert Kargon, Stuart Leslie and Erica Schoenberger, "Far Beyond Big Science: Science Regions and the Organization of Research and Development," in *Big Science: the Growth of Large-Scale Research*, eds. Peter Galison and Bruce Hevly (Stanford: Stanford University Press, 1992), 336.

In the case of Esso, the situation was slightly different. As research on the most chemically complex and logistically important hydrocarbons stalled, ARPA managers became increasingly anxious, shifting emphasis away from basic research towards hardware that could immediately be put into service. Esso's resulting technology used fuels that were less desirable from the perspective both of the Army and the fuel supplier. Instead of abandoning these systems, ARPA sought new justifications for them. The agency's formula for rapid technological results produced in an orderly, linear fashion by dedicated "basic" and "applied" research units yielded fuel cell technologies shaped more by political considerations than the requirements of the end-user.

From Hydrogen to Hydrocarbon: Redefining the Army's Fuel Cell Priorities

From 1956 to 1960, the Army's expectations for fuel cells were limited. Like British researchers, the U.S. Army's scientists and engineers were intrigued by early tests on simple hydrogen-oxygen equipment, although it was far from clear to them how such power sources could be most fruitfully employed. In the early to mid-1950s, there was no unified Army fuel cell project. The service had several research and development bureaus engaged in a variety of fuel cell experiments, drawing from its "arsenal" tradition of in-house weapons development and testing. In 1960, ARPA and the Army began an ambitious partnership that prioritized the hydrocarbon fuel cell within the service's power source program, providing the intellectual basis for an all-purpose "miracle" battery.

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[43] F.T. Bacon, "Visit by Mr. F.T. Bacon and Mr. K.E.V. Willis of NRDC to Fuel Cell Activities in the USA," July 1961, Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.672, 5.

The Army's interest in fuel cells originally related to the problem of meeting the power demands of new electronic devices. For the engineers of the Signal Corps, the revolution in "push-button warfare" required a revolution in power sources. On the atomic battlefield, the Army believed, only small bands of highly mobile soldiers equipped with the latest transistorized surveillance and communications gear could hope to survive. Army researchers complained that electronics developers often did not consider power sources as anything other than a "necessary evil."[44] For the new high-powered electronics, existing batteries were considered inadequate. Because the trend in the miniaturization of electronics was not being matched in the field of power sources, the advantages of these new compact appliances were not being fully exploited. There were also future requirements to consider. Though the White House had prohibited the Army from developing satellites prior to the launch of Sputnik, the service was actively engaged in rocket booster development and dreamed of a more active role in space.[45] Some Army researchers anticipated that missile guidance systems and the first space vehicles would also have demands for electrical power incapable of being met with existing equipment. Developing suitable power sources for these applications was a task for which they sought responsibility.[46]

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[44] Paul W. Albert, "Welcoming Address," in *Proceedings: Twelfth Annual Battery Research and Development Conference, 21-22 May 1958* (Fort Monmouth, NJ: Battery Conference Committee, 1958), 1. Eisenhower's "New Look" defense policy, introduced in 1954, was a radical departure from past military doctrine, emphasizing a much greater reliance on aircraft and missile-born nuclear weapons. Planners assumed that such weapons would be much more effective and economical than large expeditionary forces of the kind that had fought to stalemate in Korea. The various U.S. armed services envisioned fighting the "New Look" nuclear war in the 1950s in quite different ways. The Air Force was guided by the declaratory policy of "massive retaliation," an all-out attack on Soviet and Communist Chinese cities using big thermonuclear bombs carried on big intercontinental bombers and missiles. Such a war might last only hours. On the other hand, the Army's doctrine of the "tactical atom" envisioned a more limited and protracted war fought with small atomic and nuclear weapons delivered by tube and rocket artillery and short-range aircraft bombing in support of troop movements.

Faced with pressing present and future power source requirements, Army planners encouraged researchers to seek technological breakthroughs. In May 1957, the Signal Corps Engineering Laboratory's Brigadier General Earle F. Cook declared that incremental advances in power source technologies were unsatisfactory. Only the exploration of the newest processes and materials would yield the desired results.[47] In 1956 and 1957, the Army was considering solar cells and nuclear batteries, not fuel cells, in this vein.

This was reflected in the Signal Laboratory's annual power sources conference, an important bellwether of Army and industry thought on power technology. In 1957, the conference featured only one presentation relating to fuel cells while hosting two special symposia for solar and nuclear technology. That year, however, the Signal Laboratory tested a Union Carbide hydrogen fuel cell powering a small radar at Fort Huachuca, Arizona. In 1958, fuel cells featured prominently at the conference for the first time, with leading U.S. firms including Patterson-Moos, the National Carbon division of Union Carbide and General Electric making presentations of preliminary research. The tone, however, was generally equivocal. All of the featured power sources were laboratory models using pure hydrogen and oxygen, and the conferees did not mention specific requirements or applications except in the most general way.[48]

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[45] Dwayne A. Day, "Invitation to Struggle: The History of Civilian-Military Relations in Space," in *Exploring the Unknown: Selected Documents in the History of the U.S. Civilian Space Program Volume II: External Relationships*, ed. John M. Logsdon (Washington, D.C.: NASA History Office, 1996), 244-249, 255. After ARPA was stripped of its space programs in September 1959, the armed services were allowed to develop their own satellites.

[46] D. Linden, "The Next Ten Years," in *Proceedings: Tenth Annual Battery Research and Development Conference, 23 May 1956* (Fort Monmouth, NJ: Battery Conference Committee, 1956), 63-65.

[47] Earle F. Cook, "Introductory Remarks," in *Proceedings: Eleventh Annual Battery Research and Development Conference, 22-23 May 1957* (Fort Monmouth, NJ: Battery Conference Committee, 1957), 1-2.

The Army laboratories continued to study hydrogen-oxygen fuel cells despite the fact they could find few clear roles for them. In the late summer of 1960, however, ARPA and Army planners began to formally reorient the Army's research priorities so that developing a hydrocarbon fuel cell became the main goal. The rationale for the program was articulated at a conference between officials from ARPA and the Army's Ordnance Corps research and development bureau (OCRD) on 28 November 1960. During, this meeting, Urner Liddel, ARPA's assistant director for general research, requested an Army proposal for a program of energy conversion research.[49]

The resulting six-page document drafted by members of the Ordnance Corps outlined a research proposal that radically reshaped the Army's expectations of fuel cells. The OCRD officials regarded fuel cells as the most promising of all the energy conversion technologies then under consideration by ARPA. They noted that the "remarkable" increase in interest in fuel cells during 1960 was due largely to the possibility of developing a design capable of operating on petroleum and natural gas. Whereas the various Army research and development bureaus had considered applying hydrogen-oxygen fuel cells only in niche roles, the proposal made clear that a hydrocarbon fuel cell would be valuable in a variety of stationary and mobile applications in both military and civilian roles, greatly expanding the potential scope of use.[50]

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[48] Patterson-Moos' Kenneth Rapp stated that although the economics were then unclear, the hydrogen oxygen cell would compete favourably with battery systems in "mobile military applications" requiring power at the minimum weight; Rapp, "Hydrogen-Oxygen Fuel Cells," in *Proceedings: Twelfth Annual Battery Research and Development Conference, 21-22 May 1958* (Fort Monmouth, NJ: Battery Conference Committee, 1958), 11. The National Carbon representative noted that testing to date suggested that a single power source could be used to "operate a variety of different loads," lending credence to the idea of a general-purpose fuel cell. Interestingly, the National Carbon Company's program had proceeded under completely different assumptions than Brigadier General Cook had indicated. George E. Evans claimed that the fuel cell the company had unveiled in 1957 had been produced through the "laborious collection of information" and long-term testing, not "some sudden scientific breakthrough;" G.E. Evans, "An Experimental Hydrogen-Oxygen Fuel Cell System," in *Proceedings: Twelfth Annual Battery Research and Development Conference*, 5-7.

[49] Memorandum by E.G. Witting, 13 March 1961, Box 4, Project Lorraine-Energy Conversion, National Archives and Records Administration II, Greenbelt, MD.

The authors of the proposal made a number of important assumptions. They expected that hydrocarbon fuel cells would "evolve" from existing hydrogen-oxygen designs. They admitted they did not expect this to be simple. Discussions with industry revealed that little was known about the electrochemical dynamics that would attend operations with carbonaceous fuel, particularly which fuels operated best under various conditions. It was, however, clear to them that alkaline electrolytes were unsuitable for such fuels and that acid designs would have to be developed. So, too, was little known about electrodes, then a "black art." While the reaction mechanism of the oxygen electrode (cathode) in alkaline media was understood, the reaction at the anode, especially when carbonaceous fuels were used, was not. The behavior of electrodes in acid media presented further unknowns. There were also uncertainties regarding the "poisoning" effect of sulfurous fuels on electrodes.

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[50] Despite the new priority on hydrocarbon fuel cells, the Signal Laboratory continued to investigate hydrogen-oxygen fuel cells, the most important of which was the ion exchange membrane design pioneered by General Electric. Both the Signal Laboratory and ARPA aided the company's efforts to define the limitations and capabilities of the technology and the Army briefly developed its own requirement for it. In early 1961, it contracted with General Electric for one 200-watt hydrogen-fueled "backpack" system weighing 84 pounds. Despite its weight, the laboratory considered the device a "breakthrough" in power sources for "forward area radar;" U.S. Army Signal Research and Development Laboratory, "Fuel Cells for Radar Set AN/TPS-26 (XN-1)," *Research and Development Summary* 8, no. 1, 1 January 1961. The Signal Laboratory also sponsored work on the membrane fuel cell in the regenerative role for possible use in space. However, early membranes gave low current densities in fuel cells and were prone to dehydration and high electrical resistance. The Army abandoned work on membrane fuel cells around 1963 and thereafter, General Electric focused on developing them for space and terrestrial applications. In the late 1980s, Ballard Power Systems of Vancouver developed advanced membrane fuel cells, leading to a resurgence of interest in the technology.

Given the considerable gaps in the knowledge of such systems, the OCRD officials cautioned, the "present enthusiasm" for hydrocarbon fuel cells had only a "sketchy" basis.[51] Nevertheless, they recommended a program of basic research into fuels, electrolytes and electrodes, to be monitored by the Army. With three of its laboratories already pursuing their own fuel cell programs and monitoring the related industry contracts, contributing more than a third of the funds the Department of Defense had expended on fuel cell research and development to date, the Army, the OCRD officials claimed, was well-placed to administer the project.[52] What was more, the "needs of the Army" vis-à-vis the hydrocarbon fuel cell paralleled the larger commercial aspirations of industry.[53]

Despite the caveats, this Army proposal was enthusiastically endorsed and adopted by ARPA and served as the basis for Project Lorraine. ARPA's arbitration of this research and development program, however, was guided not solely by technical criteria but also by political factors. These stemmed from the vague expectations its managers had of basic science beyond a general assumption that it contributed to technological breakthroughs, often in ways that were not immediately obvious. This quest for the breakthrough in turn complicated the agency's linear organizational model of research. As the program manager of the federal government's energy conversion effort, ARPA imposed a degree of rational management on the Army's fuel cell program for the first time, inheriting nascent industrial research partnerships in which the possibilities of hydrocarbon oxidation in fuel cells were just beginning to be explored.

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[51] Memorandum, "Summary of Proposal of Research on Energy Conversion," 6 February 1961, Box 4, Project Lorraine-Energy Conversion, National Archives and Records Administration II, Greenbelt, MD.

[52] These facilities were the Signal Corps Laboratory at Fort Monmouth, New Jersey, the Harry Diamond Ordnance Fuse Laboratory in Washington, D.C., and the Engineer Laboratory at Fort Belvoir, Virginia.

[53] The Army Office of Ordnance Research (OOR), founded in 1951, became the Army Research Office (ARO) in March 1961. It was responsible for supervising the Army's entire program of basic and applied research *(Fifteenth Annual Power Sources Conference*, 2-3). The role of Ernst M. Cohn is especially noteworthy not only in this episode but in the broader history of U.S. fuel cell research and development in the 1960s. Cohn was one of the two Ordnance Corps Research and Development personnel who helped ARPA's Liddel formulate the Army's hydrocarbon fuel cell policy and probably co-authored the proposal on energy conversion. As a member of the Army Research Office, Cohn subsequently played an important role in administering this program before moving to NASA in 1962-63, where he became head of the agency's in-house fuel cell research and development program. Cohn's involvement in both Army and NASA fuel cell research over a decade and a half provides a valuable window of insight into the disparate technical challenges facing these agencies and the changing economic and technological fortunes of the federal government's fuel cell programs well into the 1970s.

Manufacturing Momentum: Research and Development in the Policy Advisory Feedback Loop

Electrochemistry, the basis of fuel cell technology, was the pauper of post-war American science. Theoretical physics, dramatically and successfully applied in the Second World War and decreed a national security priority by the federal government during the Cold War, dominated all scientific fields. Far fewer resources were available for electrochemistry, which remained relatively poorly understood. Such neglect had not always been the case. The field had flourished in the U.S. in the late nineteenth century, when storage batteries were widely used as load-levelers in early direct current central power stations in order to smooth the often uneven power output of early generators. But in the twentieth century, the practice of electrochemistry declined as reliable electromagnetic generating systems in large central stations dominated the production and distribution of electricity and as the basic automotive lead-acid storage battery was standardized in the 1920s. As the historian Richard H.

Schallenberg has observed, American electrical engineers were no longer stimulated to think in terms of electrochemical solutions to problems.[54]

Although the federal government would spend large sums on fuel cell development in the 1960s, mainly in the space program, most of this money went to contractors, doing little to foster a post-secondary or polytechnic electrochemical training base. With few career opportunities available in American industry or government, electrochemical engineering had little prestige. So unpopular was the profession that fuel cell programs in the 1960s were plagued by a labour shortage. Planners resorted to retraining physical chemists and chemical engineers and importing European electrochemists.[55]

Fuel cell development was further hindered by the reluctance of American corporations to sponsor collective research.[56] In October 1960, 20 firms (later joined by 26 more) began to support a program of fundamental research on fuel cells at the Battelle Memorial Institute in Columbus, Ohio, agreeing to contribute some $1.725 million over five years. Francis Bacon, operating in his new role as fuel cell consultant, reported that while the facility had competent staff, was well-equipped with experimental and construction facilities and had access to support from other scientific disciplines, none of the sponsoring companies was prepared to supply the institute with details of their own research on fuel cells. This forced Battelle's researchers to start virtually "from scratch."[57]

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[54] Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (Philadelphia: American Philosophical Society, 1982), 391.

[55] *Energy Research and Development and National Progress: Prepared for the Interdepartmental Energy Study by the Energy Study Group under the direction of Ali Bulent Cambel* (Washington, D.C.: U.S. Government Printing Office, 1965), 308. In the late 1960s, Pratt & Whitney asked Bacon to help them recruit electrochemical talent in Britain on their behalf; H.M. Hershenson, Assistant Director, Research and Development Laboratory to Bacon, 22 July 1968, Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, 'Leesona-Moos and P&W,' B.1147.

[56] Stuart W. Leslie and Robert H. Kargon observe this phenomenon in Frederick Terman's efforts to enlist the participation of eastern U.S. industrial firms as part of his attempt to replicate Stanford University's successful academic-industrial complex in New Jersey in the mid-1960s; Stuart W. Leslie and Robert H. Kargon, "Selling Silicon Valley: Frederick Terman's Model for Regional Advantage," *The Business History Review* 70, no. 4 (Winter 1996): 447.

It was in this environment that the U.S. government proceeded with research on the terrestrial hydrocarbon fuel cell. The lack of knowledge and expectations for a miracle power source were inversely proportional. Military and industry researchers often overgeneralized and extrapolated from what in retrospect proved to be relatively minor successes achieved in controlled laboratory conditions. What was more, expectations could be generated and amplified at any point along the complex feedback loop linking researchers in military and industrial laboratories, ARPA program managers and scientists working for the Institute for Defense Analyses: ARPA planners went to work for the IDA and vice-versa while industry leaked progress reports to IDA planners that eventually filtered back to ARPA. This led to the escalation of expectations, a tendency exacerbated by the fact the hydrocarbon fuel cell program had not originated as a unified project guided by clearly defined milestones. As in the British milieu, the fuel cell inspired curiosity. It was a solution looking for a problem. Unlike in Britain, however, the sheer size of the American defense science and technology establishment meant that novelties like the fuel cell could attract funding, and constituencies, relatively easily.

The first link in the chain of expectations for the hydrocarbon fuel cell had been forged by the Signal Research and Development Laboratory well before the Army and ARPA formally launched Project Lorraine in July 1960. The laboratory's principal researchers noted that the dream to oxidize liquid organic fuels was an old one and had long been dogged by persistent technical obstacles. In 1959 and 1960, the problem that preoccupied them most was the method by which fuel was delivered to the fuel cell. While researchers knew that fuel cells could oxidize alcohol or hydrocarbon vapours at high temperatures, this was regarded as impractical. Gaseous fuels could be stored as liquids, but converting them back to gases required special pressure regulation systems that complicated operational control and added weight and volume to fuel cell systems. Researchers wanted to be able to directly use common liquid fuels in fuel cells at room temperature.[58]

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[57] F.T. Bacon, "Visit by Mr. F.T. Bacon and Mr. K.E.V. Willis of NRDC to Fuel Cell Activities in the USA-July 1961," undated, Papers and Correspondence of Francis Thomas Bacon, Section B, Research and Development, Energy Conversion Limited, Reports, B.672 Churchill College Archives Center, University of Cambridge, Cambridge, England (hereafter cited as Bacon MS or TS). Bacon did not name the participating companies.

No less important was the chemical composition of the liquid fuels under investigation. A crucial factor in the generation of expectations was semantic confusion concerning the nomenclature of fuels that could and could not be readily consumed by fuel cells. By early 1960, all the Signal Laboratory's tests had used "organic" fuels such as alcohols, aldehydes or fatty acids, not "hydrocarbons."[59] While both classes of substance contain hydrogen and carbon, "organic" fuels have molecules that contain one oxygen atom, while "hydrocarbons" contain only carbon and hydrogen. The distinction between "organic" and "hydrocarbon" fuel was crucial because partially oxygenated organic fuels proved much easier to oxidize in fuel cells than hydrocarbons. The Signal Laboratory's experiments with "organic" fuels in half and single alkaline cells revealed that systems using basic electrolytes were very sensitive to contamination from the byproducts of oxidation. Though oxidation weas unsustainable, researchers were impressed by the fact it had occurred at all. They concluded that results would be much better on acidic fuel cell systems that had some resistance to impurities.[60]

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[58] Herbert F. Hunger, "Ion Exchange Liquid Fuel Cells," in *Proceedings: Fourteenth Annual Power Sources Conference, 17-18-19 May 1960* (Red Bank, NJ: PSC Publications Committee, 1960), 55-56.
[59] James E. Wynn, "Liquid Fuel Cells," in *Proceedings: Fourteenth Annual Power Sources Conference*, 52.

Encouraged by these early findings with organic fuels, researchers began to refer to "organic" carbonaceous and "hydrocarbon" fuels interchangeably, despite their different behaviors in fuel cells.[61] However, in late 1960, ARPA and Army planners formally declared that the goal of Project Lorraine was to develop a "hydrocarbon" fuel cell. The research proposal drafted by ARPA and Ordnance Corps personnel between late 1960 and early 1961 referred explicitly to the goal of developing fuel cells capable of converting fuels made from petroleum and natural gas. To be sure, there are significant chemical differences among the various fuels that can be derived from petroleum. And while the results of the early Signal Laboratory experiments on liquid organic fuels had in fact been preliminary, researchers were nonetheless ebullient. In the spring of 1960, Hans K. Ziegler, the laboratory's chief scientist, considered the results the most spectacular advance of a battery technology "previously considered hardly worthwhile."[62]

By fall 1961, ARPA was distributing contracts and the hydrocarbon fuel cell project, and fuel cells in general, gained a much higher profile within the Army. In his welcoming address delivered at the Power Sources Conference of 1961, Colonel Raymond H. Bates, the Signal Laboratory's commanding officer, observed that thermal energy conversion and fuel cells now constituted a major part of the symposium.[63] Despite this, the Army had still not identified specific roles for fuel cells that would directly use any kind of liquid fuel. Nor had ARPA set milestones before initiating Project Lorraine and none had been identified as late as June 1961, well after the agency began funneling money to contractors.[64]

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[60] Ibid., 55.

[61] For example, Hunger claimed that it would be possible to use "relatively inexpensive organic compounds such as hydrocarbons or partially oxygenated hydrocarbons" in fuel cells without elaborating on the nature of these fuels or the power source applications; Hunger, *Proceedings: Fourteenth Annual Power Sources Conference*, 56.

[62] Hans K. Ziegler, "Keynote Address," in *Proceedings: Fourteenth Annual Power Sources Conference*, 2.

It was not until the summer of 1962 that ARPA managers began to draft requirements and milestones for a liquid fuel system. Notably, they selected not a hydrocarbon but an alcohol. One of the earliest fundamental studies of fuel oxidation funded by Project Lorraine identified methanol as a desirable laboratory material. Although the California Research Corporation (CRC) had originally been charged with studying the process by which hydrocarbons were oxidized at the anode, its researchers found substances like propane and ethylene difficult to work with. Employing fuel cells using platinum catalysts and acid electrolytes, workers focused on formaldehyde, formic acid and methanol, the same "organic" carbonaceous compounds the Army's Signal laboratory had investigated the previous year. Of these, methanol was favored because it was "tractable." Because methanol was the simplest of the "hydrocarbon intermediates," the mechanism by which it underwent electro-oxidation was relatively easy to understand. Almost as an afterthought, the CRC's principal investigators concluded that methanol would produce high current densities when used in a fuel cell, though there would be a problem disposing of the reaction products.[65]

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[63] Raymond H. Bates, "Welcome," in *Proceedings: Fifteenth Annual Power Sources Conference, 9-11 May 1961* (Red Bank, NJ: PSC Publications Committee, 1961), 1.

[64] Memorandum, "Lorraine: Project Objectives," 9 June 1961, Box 4, Project Lorraine-Energy Conversion, National Archives and Records Administration II, College Park, MD.

Project managers at ARPA agreed that methanol presented fewer obstacles to electrochemical engineering. While the ultimate goal remained perfecting hydrocarbon oxidation, planners recognized that this would take time to master. ARPA directed General Electric to concentrate on this more complex fuel cell system, while Esso was made responsible for developing a methanol fuel cell employing an acidic electrolyte. This now became an important interim goal. The successful development of a laboratory device that could operate on carbonaceous fuel and air for an extended period would constitute a breakthrough according to George W. Rathjens, then ARPA's chief scientist and deputy director.[66] A professor of chemistry and staff member of the White House science advisory apparatus specializing in military technology, Rathjens did not specify how this would aid the program of basic hydrocarbon research. Notably, his directive seemed to straddle the line between "physical principles" and "fundamental engineering principles."

Flight or Fight: Fuel Cell Technology and ARPA's Mission Philosophy

The shift in emphasis from basic research to hardware in the energy conversion program has been interpreted by the official ARPA history as a move by Ruina to extricate the agency from a field he believed offered no long-term promise. By "spinning off" fuel cells, that is, producing prototype hardware and turning it over to the armed services for trials and further development, the theory goes, Ruina was attempting to end ARPA's involvement with the technology. The matter, however, seems a good deal more complex than this. The history's author, Richard J. Barber Associates, did not cite correspondence to or from Ruina, relaying instead on a single document dating from 1963, not 1961, the year the "spin-off" decision was ostensibly made. This status report from the Materials Sciences Office (MSO) was equivocal on the issue of "spin-off." While ARPA was able to completely discharge its responsibilities for other unpromising energy conversion technologies such as thermionics in 1961, the MSO report recollected that planners had only considered the *possibility* of "spinning-off" fuel cells over the next two years owing to the immature state of the technology.[67] In fact, ARPA's position on technology development shifted gradually over time in response to laboratory developments. Indeed, the process of "spinning off" fuel cells was lengthy, lasting from 1961 to 1965.

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[65] R.P. Buck, L.R. Griffith, R.T. MacDonald and M.J. Schlatter, "Mechanisms and Kinetics of Reactive Groups in Organic Fuels," in *Proceedings: Fifteenth Annual Power Sources Conference*, 16-20.

[66] George W. Rathjens to Chief, Research and Development, Department of the Army, 26 July 1961, Box 2, AO 247-Esso Research and Engineering Company, National Archives and Records Administration II, College Park, MD.

The question then becomes why it took so long for ARPA to rid itself of a technology its director believed had no potential. The answer is that within certain quarters of ARPA, industry, the IDA and the Army, there were people who thought that fuel cells had great promise as an energy conversion technology and wanted to devote more effort to the program.[68] I argue that ARPA's move to develop fuel cell hardware was less a political tactic to relieve itself of technological responsibility and return the agency purely to the administration of basic research than a means of reconciling the disparate interests that had become associated with the technology during the agency's transition period.

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[67] "Status Report-Project Lorraine," 31 October 1963, Box 4, Project Lorraine-Energy Conversion, 1.

[68] Richard J. Barber Associates acknowledged that the shift to early hardware development provoked considerable debate within ARPA's MSO. A 1961 review conducted for Rathjens argued that more time and resources should be committed to basic research and that an effort should be made to involve the university interdisciplinary laboratory programs; Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974*, V-55-56.

As I shall demonstrate, in developing short and long-term fuel cell programs, one oriented towards prototype hardware, the other remaining an effort in basic research, ARPA balanced expectations among IDA staffers and the Army for a technological payoff while conforming to its own primary commitment to basic science. ARPA managers thus conceived the methanol fuel cell as a kind of technological hedge should the troubled hydrocarbon electro-oxidation research fail. They then set about justifying it. It was true that methanol was not a hydrocarbon logistics fuel, and so a methanol fuel cell could not offer "economy." Nevertheless, military planners reasoned that high power and silent operation were additional desirable attributes of fuel cell technology.[69] Moreover, claimed ARPA managers, the technology was versatile owing to its flexible fuel capability and, consequently, possessed immediate utility. Since it was likely to function even better on hydrogen, they asserted, a methanol fuel cell could also serve as the basis for an "indirect" system, consuming hydrogen-rich gas converted from hydrocarbons by a reformer.[70] Such a system would be useful even if the direct hydrocarbon project proved successful. This, in turn, required reforming technology, another item not originally on ARPA's agenda. Without this auxiliary device, the methanol cell, assuming that its direct fuel injection system could be made to work reliably, remained a special-purpose, small-volume technology. This was an important consideration, given that industry's commercial aspirations, and the military's own requirements, called for a general-purpose hydrocarbon fuel cell.

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[69] Ziegler, "Keynote Address," in *Proceedings: Fourteenth Annual Power Sources Conference*, 2.
[70] Memorandum by Charles F. Yost, 13 July 1962, Box 2, AO 247-Esso Research & Engineering.

Electrochemical Dilettantes: Compartmentalized Expertise and the Institute for Defense Analyses

ARPA's selection of Esso and General Electric as the lead industrial contractors for the hydrocarbon program was based on its perception that these companies were leaders in the fledgling fuel cell field. Both companies had been conducting fuel cell research for several years and General Electric was widely thought of as a dominant player with its pioneering ion exchange membrane design. Neither, however, had much theoretical experience in the field. As one noted chemist observed at the time, many American companies had begun fuel cell research with very little knowledge of electrochemistry and its related fields.[71] Further, corporate interests in fuel cells did not necessarily correspond with the imperatives of the basic research program as ARPA understood them. Building a fuel cell entailed a knowledge of chemistry, electrical and electrochemical engineering and metallurgy, as British researchers had learned. Although ARPA planners recognized the technology's interdisciplinary nature, they distributed funding across a multitude of companies, each of which was responsible for solving very specific scientific and techno-scientific problems.[72]

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[71] Ernest Yeager to F.T. Bacon, 2 February 1961, Bacon MS, Section G, Correspondence, Fuel Cell Correspondence, G.125.

[72] The program for fiscal year 1961 included a total of 44 separate contracts distributed to 30 companies in six research areas: solar cells, electrochemistry, thermionic converters, thermoelectricity, magnetohydrodynamics and ancillary problems. Total funding was $4.6 million, of which electrochemistry absorbed the single largest share, with $1.37 million. Overall, General Electric had by far the largest share with six contracts worth $930,000, followed by General Atomic with three contracts worth $481,000, RCA with two contracts worth $373,000, MIT with five contracts worth $315,000 and Monsanto with two contracts worth $152,000. The distribution was somewhat more even in electrochemistry, though General Electric once more dominated. Of 14 contracts, General Electric held two worth $360,000; Memorandum, "General Comments," undated, Box 4, Project Lorraine-Energy Conversion.

Likely the result of a combination of factors - the reluctance of private companies to cooperate with potential competitors and the Pentagon's tendency to spread contracts across as wide a spectrum of industry as possible to build political support and use the linear method of accounting for "basic research," "applied research" and "development" - this had the effect of compartmentalizing expertise.

The problem was that many of the technical problems parceled out to the array of contractors turned out to be interrelated. While neither Esso nor General Electric possessed the full range of skills necessary for hydrocarbon fuel cell research, in some ways their respective capabilities were complementary. The resulting reductive perspectives on the program's overall progress were conveyed via the policy feedback loop linking individual contractors, the IDA and ARPA. These communications were paralleled by the marked shift in emphasis within Project Lorraine from "physical principles" to "fundamental engineering principles" and "hardware" that began in the first half of 1962.

Esso, like Shell, began investigating fuel cells in the late 1950s to familiarize itself with the technology in order to supply suitable fuels should these power sources be commercialized. The company was less interested in current output generated by the chemical reactor unit itself than in determining rates of fuel consumption.[73] Consequently, fuel cell hardware was not Esso's *forte* and the company was staking its investments in Project Lorraine on technological developments made by other parties. Now, it was in charge of developing a technology for which only niche roles, and thus small volumes of fuel, seemed likely. This ran contrary to Esso's rationale for involvement in the first place. The only thing that linked the company to its goals was the assumption that the methanol fuel cell would somehow provide experience of use in the hydrocarbon project.[74]

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[73] J.C. Frost, "Report on Visit to the United States from 10-24 September," 2 October 1959, Bacon TS, Section B, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B.318, 2.

Conversely, General Electric's main concern was hardware. The company had great hopes for its fuel cell systems. Throughout the 1960s, it was one of the most persistent boosters of the technology. Although it saw the military as its main market, it hoped to adapt these fuel cells for the civilian market. While ARPA made General Electric responsible for developing the hydrocarbon fuel cell, the company was moving on untrodden ground. According to Bacon, General Electric had "no skills" in hydrocarbon conversion and was relying on oil companies to supply the relevant knowledge base.[75] Despite this, General Electric was optimistic about the prospects for the various fuel cell systems it had under development in 1962, particularly the hydrocarbon program. Its officials made sure to convey this impression to the Institute for Defense Analyses.

The relationship between General Electric and the IDA illustrates how the science and technology policy advisory system inflated expectations of the technical possibilities of a hydrocarbon fuel cell. It also reveals the degree to which advice was the product of non-technical factors such as inter-departmental politics within the advisory establishment. While the possibility of using a hydrocarbon fuel cell as a power source for electric vehicles was discussed within the Army and the IDA throughout 1962, it was also the subject of some controversy. In the late summer, two IDA analysts disputed the feasibility of this application, sending conflicting signals back to ARPA. The incident centered on an early draft of a report on progress in power source research that was to have been jointly prepared by the analysts. The report had in fact been completed by one without the other's input and, without the latter's knowledge or consent, had sent it to the Director of Defense Research & Engineering.

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[74] Esso's philosophy of fuel cell technology can be gauged by an investigation it undertook in 1961. The company's Research & Engineering unit succeeded in electrochemically oxidizing ethane in a modified alkaline Bacon cell. For Esso researchers, the salient point was that they had successfully demonstrated that a saturated hydrocarbon could be reduced to carbon dioxide at relatively mild temperatures and pressures. They claimed they had proved hydrocarbons could "meet one of the primary requirements for fuel cell application: complete oxidation." They were less concerned with the fact that ethane is a light hydrocarbon not then widely used either by industry or the military. The researchers were also aware that making a fuel cell durable depended on developing either a device that would cleanse the electrolyte of impurities or an electrolyte that would reject carbon dioxide. However, the laboratory regarded these as problems for others to solve. The import of Esso Research & Engineering's claims thus could only be understood within the highly reductive context of success its researchers had defined; C.E. Heath and C.H. Worsham, "The Electrochemical Oxidation of Hydrocarbons in a Fuel Cell," in *Fuel Cells, Volume II*, ed. G.J. Young, 189.

[75] Bacon, "Visit by Mr. F.T. Bacon and Mr. K.E.V. Willis of NRDC to Fuel Cell Activities in the USA-July 1961," 5.

This report, authored by a scientist named Robert Hamilton, was strongly critical of ARPA's management of the fuel cell program. Citing poor project selection, inadequate information distribution and nebulous task orders, Hamilton called for the assignment of an administrative aide to the manager of Project Lorraine. More importantly, he declared that there was no justification on a cost-effectiveness basis to support the replacement of internal combustion vehicles with fuel cell electric vehicles. Hamilton recommended cutting funds from the fuel cell portion of the program by 41 per cent, from $1.7 million to $1 million for Fiscal Year 1963.[76]

The would-be co-author, G.C. Szego, was outraged. He wrote a dissenting report in the form of a memorandum to his IDA superior, demanding that Hamilton's views "not be presented to ARPA" for they might well lead to the cancellation of a valuable program. Szego supported developing the automotive fuel cell and contested

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[76] G.C. Szego to S.S. Penner, 20 September 1962, Box 4, Project Lorraine-Energy Conversion, 2-3, National Archives and Records Administration II, Greenbelt, MD.

Hamilton's claim that the Army's fuel costs were so low as to obviate the need for such a power source. Citing personal communications with Ernst Cohn of the Army Research Office among other informants, Szego claimed that Hamilton's cost figure of two cents per mile to operate an Army truck was "hopelessly and ridiculously incorrect." According to Szego's correspondents, each gallon of gasoline supplied to U.S. military forces in Korea during the 1950-1953 war had cost $10.[77] Szego calculated that fuel cell electric trucks employing regenerative braking would save about $1650 per battlefield day per 200-horsepower truck. Citing figures supplied by General Electric, Szego claimed fuel cells would cost between $300-$500 per kilowatt by 1970, a figure he considered conservative. The company forecast that the cost might be even lower by the mid-1970s, less than $100 per kilowatt.[78] Szego also believed fuel cell manufacture lent itself to cheap methods of mass-production including parts stamping. The most serious unavoidable expense was the platinum catalyst, which represented about 20 per cent of the total capital cost. This, he claimed, could easily be recycled from spent fuel cells.

Szego recommended increasing ARPA's fuel cell budget for fiscal year 1963 by $700,000 to a total of $2.4 million and accelerating and expanding the hydrocarbon program, a position that paralleled the view of the Army's Engineer Research and Development Laboratories. This meant paying more attention to the two ways hydrocarbons were used in fuel cells: the direct approach, the oxidation of fuel directly injected in the fuel cell, and the indirect approach, reforming hydrocarbons into hydrogen, which could then be fed into the fuel cell. The direct approach was more desirable, said Szego, but the Engelhard company's new hydrocarbon reformer made the indirect method more viable in the near term. In essence, Szego reinforced the bias towards building hardware.

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[77] Ibid., 3.
[78] Ibid., 3-5.

This interdepartmental memo is important for what it reveals of the ways the civilian think-tanks informing ARPA's energy conversion policy formulated their advice. Szego had obtained the $300-$500 per kilowatt figure from General Electric's sales representative. What was more, these were *projected* costs that assumed major technological and manufacturing advances. The sales representative had qualified his estimate, noting that predicting future costs was difficult, particularly since the fuel cells General Electric was currently developing were designed for special applications and would bear only a "limited resemblance" to the types it planned to manufacture in quantity.[79] Moreover, Szego had cited high current densities of General Electric fuel cells as evidence of progress, yet these had been obtained on an alkaline fuel cell using hydrogen. This was precisely the technology the military and industry were working to replace because of its susceptibility to contaminants.[80]

Crucially, Szego did not address the specific electrochemical issues relating to the oxidation of hydrocarbons in fuel cells that were at the very core of the electrochemical portion of Project Lorraine, including relative costs of the different materials and fuels that direct and indirect systems would require in Army service. In the sole instance where Szego actually referred to the economic and technological implications of a specific fuel, his conclusions contradicted the core premise of Project Lorraine. He touted methanol because it placed limited demands on the existing industrial infrastructure, being a cheap chemical already produced in quantity as a byproduct of petrochemical refining and wood processing. Methanol could also be easily stored at room temperature. However, the introduction of this fuel into the Army supply chain, he admitted, was "not especially desirable."[81] This was not an academic point, given that a prime justification for the hydrocarbon fuel cell project was that it would simplify Army logistics.

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[79] J.W. Babcock to George Szego, 17 September 1962, Box 4, Project Lorraine-Energy Conversion, 1.
[80] Szego to Penner, 20 September 1962, 6.

In outlining short and long-term technological options, Szego legitimized the simplest possible engineering solutions. The question of whether the interim system met the requirements of the end user was a secondary consideration. Though he styled his appeal as a macro-economic analysis that considered trade-offs in cost and performance, Szego reported only good news wherever it was to be found among the vast range of electrochemical, logistical and materials factors. Finally, Szego's own position on hydrocarbon research had been shaped as much by the dispute over the jurisdiction of expertise in the IDA as by the facts as he saw them. He and his colleague had agreed at the outset to share management responsibilities: Hamilton dealt with magnetohydrodynamic, thermionic and photovoltaic systems and Szego was responsible for all electrochemical and/or thermoelectric technologies.[82] Szego's indignation stemmed not only from the fact that Hamilton had failed to consult him in submitting an early draft to the DDR&E, but also that he had made a major policy judgment on issues that were not within his purview.

Ultimately, Szego's views prevailed within the IDA. While scientists had been stymied in the early stages of the hydrocarbon fuel cell research program, expectations for a fuel cell that could power military electric vehicles mounted. In October 1962, an ARPA internal memorandum stated that the program's ultimate goal was to electro-oxidize logistics fuels including "combat gas," diesel oil and jet fuel. In December, another internal memorandum couched expectations even more explicitly. A hydrocarbon fuel cell was to be made available for "widespread terrestrial military application," especially in vehicles. By producing fuel cells with high power densities capable of using "common liquid fuels," such power sources would halve the fuel requirements of an armored division.[83] The timeline for the program was reset to five years, a major extension of previous estimates.

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[81] Ibid., 2.
[82] Ibid., 6.

The shift in emphasis from "physical principles" to "fundamental engineering principles" to "hardware" within Project Lorraine occurred as the result of a complex mix of political and physical-material considerations. This linear movement unfolded not as the result of scientific progress but rather the lack of it. Researchers had quickly learned that liquid logistics hydrocarbons could not easily be directly oxidized in a fuel cell. But the program was not cancelled. Instead, ARPA, reinforced by the IDA, decided to take a technological short-cut, funding hardware it believed could be more easily developed in the short-term.

In addition to supporting Esso's direct methanol fuel cell, ARPA decided to invest in a reformer-fuel cell system, a "one-shot" effort designed as an expedient way to use "field grade fuels."[84] For this program, the agency would not fund research but instead purchase a complete Engelhard reformer that was to be integrated with an

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[83] Memorandum, anonymous, December 1962, Box 4, Project Lorraine-Energy Conversion, National Archives and Records Administration II, College Park, MD.
[84] Yost to R.L. Sproull, "Subject: Project Lorraine," 12 September 1963, Box 4, Project Lorraine-Energy Conversion.

Allis-Chalmers five-kilowatt alkaline fuel cell. This device was to be transferred to the Army Engineer Research and Development laboratory.[85] In committing to the Esso methanol fuel cell and the Allis-Chalmers/Engelhard system as interim solutions, ARPA adopted the additional role of program manager of a technology development program involving the subsidization of completed components, a considerable departure from its original function as overseer of a basic research program.[86]

Pressure to Produce: Quantifying Success in Basic Hydrocarbon Research

In the rush to produce "definite tangible results" in the hydrocarbon oxidation program, ARPA, influenced by the IDA, began to take on new roles it had not anticipated at the outset. By late 1962, ARPA managers had begun to refer to Project Lorraine as an "applied research project" aimed at "filling gaps" in basic research that the armed services could not meet, a use of language illustrating their ambiguous understanding of the concepts of "research" and "development."[87] While the hydrocarbon aspect of the program remained concerned largely with "physical principles," ARPA's immediate priority switched to developing methanol fuel cell hardware. In creating this interim program, the agency tacitly acknowledged that the linear organization of research was inadequate and that there was an important techno-scientific aspect to the program.

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[85] Charles F. Yost to J.P. Ruina, "Subject: Expansion of Areas in the Enery Conversion Program (Lorraine): Hydrogen-Reformer Fuel Cell Unit," 16 October 1962, Box 4, Project Lorraine-Energy Conversion.

[86] ARPA's gradual emphasis on hardware is reflected in its summary lists of funding disbursements to contractors. In 1960 and 1961, it simply grouped all fuel cell contractors together under the rubric of "electrochemistry." By 1963, it classified fuel cell contractors according under those working on hardware, or "complete systems" (General Electric, Esso and Allis-Chalmers/Engelhard), components, or "catalysts" (Monsanto and California Research Corporation) and "basic work" (Stanford University, General Atomic, AMOCO, Tyco, Westinghouse and the University of California); "General Comments," undated, 3-4, "Status Report-Project Lorraine," 31 October 1963, Box 4, Project Lorraine-Energy Conversion, 7.

[87] "Objectives and Schedules for Project Lorraine," undated (placement in the chronological arrangement of ARPA's document collection suggests that it was written in the late fall or early winter of 1962), Box 4, Project Lorraine-Energy Conversion.

Yet although ARPA was willing to promote "applied research," its managers still believed in the efficacy of linear management and continued to judge and fund projects accordingly. Project Lorraine's hydrocarbon fuel cell effort was divided among the industrial research laboratories of three firms: the American Oil Company and the California Research Corporation dealt with the more "basic aspects," while General Electric carried out work that was "somewhat more applied in nature."[88] In turn, General Electric's program involved two laboratories that by early 1961 had been organized according to a linear division of labor. The company's famous Research Laboratory in Schenectady, New York was generally responsible for "science;" the Direct Energy Conversion Operation (DECO) in Lynn, Massachusetts, managed by the Army's Engineer Research and Development Laboratory, had been set up to support development and manufacturing.[89] ARPA's support for "applied" activities in General Electric's hydrocarbon fuel cell program was contingent on progress in "basic" research. As fuel cell workers would discover, however, distinguishing between a search for "physical principles" and "fundamental engineering principles" in fuel cell research and development was not easy.

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[88] Memorandum by Yost, "Renewal of Program in Electrochemistry, ARPA Order 247, General Electric Company, Contract DA-44-009, ENG-4853," 13 August 1962, Box 2, AO 247-General Electric.

[89] In some ways, the relationship between General Electric's Research Laboratory and the company's various production divisions resembled that between the British Electrical Research Association and its constituent industries. Before 1946, GE's various departments were not required to contribute to the Research Laboratory if they thought they had nothing to gain by the research. Consequently, the Research Laboratory had to solicit the divisions for funds. After the war, the laboratory's director C. G. Suits and company president Charles E. Wilson levied a compulsory "tax" on all divisions to fund the Research Laboratory's operations; George Wise, "Science at General Electric," *Physics Today* (December 1984): 57-58.

As with Esso, General Electric's first fuel experiments in Project Lorraine involved substances that were easily oxidized and produced high current densities. ARPA managers initially encouraged experiments on light, rare hydrocarbons in the belief that this would provide valuable experience relevant for the more chemically complex logistics fuels.[90] The question of whether the findings obtained from these fuels were relevant for logistics fuels was not raised until well after experiments had started. Further, contract renewal was subject to annual progress reviews.

The first experiments conducted by the Schenectady laboratory employed the gaseous hydrocarbons propane, propylene and cyclopropane in acidic fuel cells using platinum catalyst. Of these fuels, propane was the cheapest. However, cyclopropane proved the most reactive and so became the only one of the three hydrocarbons that the Schenectady laboratory had been able to fully electro-oxidize by the summer of 1962. ARPA managers regarded this as a success. It was true, noted Charles F. Yost, the agency's director for materials sciences, that cyclopropane was not a logistics fuel and was most commonly employed as an anesthetic. Nevertheless, he claimed, its use in a fuel cell represented a step forward in learning how to directly electro-oxidize common liquid fuels.[91]

Yost did not elaborate how experience gained using a gas was relevant for systems employing liquid fuels. Nevertheless, the Research Laboratory's contract was extended for another year. It was charged now with understanding the "unique" activity exhibited by cyclopropane and achieving equal or better performance with liquid hydrocarbons.[92] In fact, ARPA and Army administrators were dissatisfied. They felt that work on hydrocarbons like propane had not progressed rapidly enough to warrant the intensification of "applied" research. While ARPA fully funded the Research Laboratory, it decided to provide only $200,000 of the $500,000 requested by the "applied" DECO laboratory.[93]

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[90] J.P. Ruina to Chief, Research and Development, Department of the Army, 7 June 1961, Box 2, AO 247-General Electric.

[91] General Electric, "Saturated Hydrocarbon Fuel Cell Program (ERDL), Quarterly Letter Report Number 1, December 1, 1961-March 31, 1962," undated, Box 2, AO 247-General Electric, 2, National Archives and Records Administration II, College Park, MD; Memorandum by Charles F. Yost, "Renewal of Program in Electrochemistry, ARPA Order 247, General Electric Company, Contract DA-44-009, ENG-4853,"13 August 1962, Box 2, AO 247-General Electric.

This funding imbalance, premised on the linear assumption that progress in basic research preceded progress in applied research, misconstrued General Electric's own evolving understanding of the techno-scientific nature of the research and development program. The "basic" research conducted at the Research Laboratory, involving the testing of the reactivity of various hydrocarbons with a variety of electrocatalytic materials, had a strong technological aspect.[94] Later stages involved investigating the "performance characteristics" of actual fuel cells. Conversely, the "applied" DECO laboratory was responsible for exploring the complete range of physical phenomena manifested in acid fuel cells using saturated hydrocarbons over time.[95] While the work at the Research Laboratory sought promising configurations of materials that produced good current densities, the DECO operation was concerned with the consequences of long-term operation including corrosion rates in fully integrated fuel cells. Its researchers described their work as "fundamental chemical engineering," a term capturing something of the techno-scientific essence of these activities.[96]

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[92] Ruina to Chief, Research and Development, Department of the Army, 25 September 1962, Box 2, AO 247-General Electric.
[93] Memorandum by Yost, "Subject: Increased Funding For Applied Fuel Cell Research at General Electric-ARPA Order 247, Amendment 5," 8 April 1963, Box 2, AO 247-General Electric.
[94] General Electric, "Saturated Hydrocarbon Fuel Cell Program (ERDL), Quarterly Letter Report Number 3, January 1, 1963-March 31, 1963," undated, Box 2, AO 247-General Electric, 2-4.
[95] Ibid., 8.

While the decision of the Army and ARPA to withhold funds from DECO may have inspired the Research Laboratory to expedite its efforts in propane electro-oxidation, the plan also forced the two laboratories to operate as independent entities rather than as a unit. As a result, General Electric chose not to immediately expand DECO's testing installations, which remained incomplete. While it is unclear how much, if any, ARPA money was available for construction at the DECO facility, the agency had prohibited the use of its funds for construction at the Schenectady laboratory.[97] ARPA's task orders for the renewal of the General Electric contract stipulated only that the company "operate" a ten-station testing facility, mentioning nothing about construction costs and adding that only a "minor effort" should be made in evaluating fuel cells.[98]

With durability testing contingent on a breakthrough in the basic sector of the program and with General Electric bearing at least some of the costs for a testing program that ARPA had accorded a low priority, the company had little incentive to invest in the DECO laboratory. It made no sense to build testing facilities if there was nothing worthwhile to test. Consequently, these facilities were not prepared for the "major state of the art advance" in basic research at Schenectady that came in late February and early March. Researchers succeeded in electro-oxidizing propane and normal or n-hexane, a liquid hydrocarbon. In ARPA's estimation, this justified

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[96] Ibid., 6.

[97] J.P. Ruina to Chief, Research and Development, Department of the Army, 7 June 1961, Box 2, AO 247-General Electric.

[98] R.L. Sproull to Commanding General, U.S. Army Materiel Command, 21 November 1963, Box 2, AO 247-General Electric.

"intensive applied research."[99] However, work in preparing installations for durability testing was barely underway at Lynn by late spring. Only one test stand had been completed, though construction on three more was planned. As a result, a backlog of completed electrodes accumulated "pending the completion of test hardware construction."[100] While a handful of acid cells using propane and various types of platinum catalysts had been tested, "very limited" life data had been produced.[101]

Here again was a case in which considerable effort was devoted to fuel cell inputs that had some favorable characteristics, but also shortcomings that offset the advantages. The "breakthrough" revealed how fuel cell laboratory communities employed simplified tests in controlled conditions. The Research Laboratory workers had succeeded in oxidizing both a gaseous and a liquid hydrocarbon. This was the first time a liquid hydrocarbon had achieved high power output in a fuel cell, an event of special importance to ARPA owing to the handling and storage difficulties presented by gaseous fuels. Though this was an important logistical consideration, n-hexane was not a logistics fuel but rather a volatile industrial solvent that quickly vaporized in exposed conditions. As such, it did not lend itself to the ease of handling that made cheap liquid fuels in general so desirable for industry and the military.

There were more problems to come. By 1963, the Research Laboratory was testing heavier oily hydrocarbons representative of the logistics fuels in acidic fuel cells employing platinum catalyst. By the spring, researchers knew that these substances posed a far greater challenge in chemical engineering than the light hydrocarbons selected by ARPA for early demonstration programs. They reported that the performance of n-hexadecane, an important constituent of diesel oil, was only 20 per cent of that of propane and butane when using an acid electrolyte and platinum catalyst.[102] That such low performance was obtained from a component of a logistics fuel using the most active known catalyst should have provided cause to disquiet researchers managers. The fact that diesel and jet fuel were complex compounds with a variety of chemical additives hinted of much more difficult electrochemical engineering to come. In early 1963, industry and Army researchers did not yet know what substances in such fuels could be completely electro-oxidized to carbon dioxide and water, producing useful electric current, and which would remain as a chemical soup within the fuel cell reactor, contaminating the electrolyte and electrodes. Despite these unknowns, program managers from both agencies were preoccupied by General Electric's latest success with light hydrocarbons. On 25 March, the U.S. Army Engineer Research and Development Laboratories recommended releasing the monies withheld from the DECO laboratory so that it could "take advantage" of the Research Laboratory's advances.[103] Planners at ARPA concurred on 8 April, adding that an additional $300,000 be made available to carry the program through to its completion date of 31 December 1963.[104]

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[99] Oscar P. Cleaver to J.P. Ruina, Director, Advanced Research Projects Agency, 25 March 1963, Box 2, AO 247-General Electric.
[100] General Electric, "Quarterly Letter Report Number 3, January 1 1963-March 31 1963," undated, Box 2, AO 247-General Electric, 8-9.
[101] Ibid., 9.

General Electric wasted no time in promoting its latest advance in light hydrocarbon oxidation. It announced a major press conference and technology demonstration to be held in New York on 23 April 1963. C.G. Suits, a physicist and the company's vice-president and director of research between 1945 and 1965, went so far as to invite Harold Brown, the Director of Defense Research and Engineering, the organization that oversaw ARPA's operations.[105] In the event, the contradictions presented by General Electric's technology program were apparent even when refracted through the lens of the business media. As reported in *The Wall Street Journal,* the new fuel cell used "inexpensive fuels," propane and natural gas, at an efficiency of 40 to 50 per cent. The article stated that General Electric had advanced closer to "practical commercial" applications, yet also observed that the fuel cell's use of platinum catalysts "precluded" it from commercial exploitation, restricting it to military use. The article finished by quoting company officials as claiming the technology would also operate on diesel, gasoline and kerosene, although additives in these fuels reduced the efficiency and operating life of the cell.[106]

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[102] General Electric, "Quarterly Letter Report Number 3, January 1 1963-March 31 1963," undated, Box 2, AO 247-General Electric, 3.

[103] Cleaver to Director, Advanced Research Projects Agency, 25 March 1963. Interestingly, the Army Engineering laboratory's projected yearly expenditures for both General Electric laboratories in Fiscal Year 1964 were significantly higher for the DECO laboratory ($600,000) than for the Research Laboratory ($400,000). This suggests that at least some Army planners were thinking in terms of redressing a perceived imbalance in program funding.

[104] Yost, 8 April 1963.

Setting aside for the moment the last contentious claim, this reportage revealed the paradox of a technology possessing some features attractive for civil use and others perhaps suitable for military requirements, but yet *as a system* unfit for any specific application, civilian or military. Too expensive for commercial use owing to its reliance on platinum catalyst, the device used fuels that, while cheap in comparison to hydrogen, were not attractive from the perspective of military logistics. Given General Electric's very limited work on heavy hydrocarbons up to that point, the company's assertion that these fuels could be used with some lifetime and performance penalties amounted to little more than boosterism.

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[105] C.G. Suits to Harold Brown, 27 March 1963; Brown to Suits, 12 April 1963, Box 2, AO 247-General Electric. Brown politely declined the offer on the grounds that he was scheduled to appear before the House Appropriations Subcommittee on that date.
[106] "GE Fuel Cell Advances," *The Wall Street Journal*, 24 April 1963.

Nevertheless, such claims led some in the electrochemical community to believe that the dream of a hydrocarbon fuel cell had been realized. In a congratulatory letter to H.A. Liebhafsky, the leader of the Research Laboratory's electrochemical team, Francis Bacon lauded General Electric's "great achievement," the "ultimate objective" that researchers had been working towards for so long. While Bacon admitted he had been skeptical that such a feat was possible, "now we know without doubt it can be done."[107]

Blind Faith and the Black Box

For the managers of Project Lorraine's hydrocarbon fuel cell program, 1963 began auspiciously even before General Electric announced its "breakthrough" in the spring. ARPA officials took heart from NASA's well-funded and highly publicized aerospace fuel cell program. To John H. Huth of ARPA's Materials Sciences Office, the development of space fuel cell hardware was a positive sign for the terrestrial hydrocarbon fuel cell program, noting in an interdepartmental memo that terrestrial systems were "less exotic" than their aerospace counterparts, though they had to be built more ruggedly.[108] This reflected the view of NASA, the fuel cell community and the business media that technologies capable of withstanding the harsh environment of space surely must be able to meet the requirements of commercial industry and provide benefits to the consumer market through a terrestrial "spin-off."[109]

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[107] F.T. Bacon to H.A. Liebhafsky, 29 May 1963, Bacon TS, Section G, Correspondence, Fuel Cell Correspondence, G.130.

[108] John H. Huth, "Program Plan for Electrochemistry: Program Plan No. 4," 1 February 1963, Box 2, AO 247-Monsanto Research Corporation (DA 36-039-SC-88945), 1, National Archives and Records Administration II, College Park, MD.

Moreover, Huth suggested, the reasons hydrocarbon fuel cells lagged five to ten years behind hydrogen fuel cells had to do more with institutional priorities than with physical obstacles. While a major effort had been launched in the space program, he claimed, the terrestrial fuel cell effort, ostensibly relevant for the entire Department of Defense, had received much less support and would have stalled completely were it not for ARPA. More resources for terrestrial fuel cell research, Huth suggested, might produce results as dramatic as in the space program.[110] This claim well illustrated the technological terms by which ARPA judged success and revealed a facile understanding both of the electrochemical issues at stake and actual progress within NASA's fuel cell program.

But as 1963 progressed, ARPA managers began to receive conflicting signals from contractors, systems analysts and military planners regarding the state of the policy of the technological hedge, the concurrent development of short and long-term projects. The Power Sources Conference held in May featured mixed accounts of the latest results in fuel cell work. Esso's Research Laboratory was bullish about its methanol fuel cell. The previous year, its engineers had been concerned with complications arising from directly injecting fuel into the electrolyte, considered to be the major source of contamination. While initial tests had occurred on individual half-cells, not complete fuel cells, Esso researchers interpreted the results as evidence that the carbonaceous fuel-air mixture would work without losing efficiency as a result of its interaction.[111] Now, they believed the odds of developing fuel cells capable of 60 per cent efficiency in "widespread military application" were "excellent."[112]

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[109] Walter Guzzardi, Jr., "The Company Astride Two Worlds," in *The Space Industry: America's Newest Giant* (Englewood Cliffs, NJ: Prentice-Hall, 1962), 115-116.
[110] Huth, "Program Plan for Electrochemistry: Program Plan No. 4," 1.

Ernst Cohn, formerly of the Ordnance Corps and the Chemical and Materials Branch of the Army Research Office and now in charge of NASA's in-house fuel cell program, delivered a generally positive report on the aerospace cells being developed for the Gemini and Apollo spacecraft.[113] Most optimistic of all were representatives from the Institute for Defense Analyses and the Army. They invoked the hydrocarbon fuel cell as a kind of miracle battery. Notably, the IDA was represented by G.C. Szego, not his more circumspect colleague Robert Hamilton. In a presentation that elaborated themes outlined in his report to his supervisor the previous September, Szego sketched a blueprint of the battlefield of the future where hydrocarbon fuel cell electric combat vehicles would bring about a revolution in logistics. As in his memorandum, he based his assessment on future developments in fuel cell technology. In fact, he was much more concerned with electric drive than the fuel cell power source itself, paying little attention to the electrochemical issues attending the most recent laboratory developments.[114]

Similar assumptions informed the Army's official view of the hydrocarbon fuel cell program. The service's fuel cell work was conducted by three organizations: the Harry Diamond Laboratories in Washington, D.C., Electronics Command's Components Laboratory (ECL) at Fort Monmouth, New Jersey, and Mobility

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[111] Barry L. Tarmy, "Methanol Fuel Cells," in *Proceedings: Sixteenth Annual Power Sources Conference, 22-24 May 1962* (Red Bank, NJ: PSC Publications Committee, 1962), 30-31.
[112] C.E. Heath, "The Methanol-Air Fuel Cell," in *Proceedings: Seventeenth Annual Power Sources Conference, 21-23 May 1963* (Red Bank, NJ: PSC Publications Committee, 1963), 96-97.
[113] Ernst M. Cohn, "Space Applications," in *Proceedings: Seventeenth Annual Power Sources*, 86-87.
[114] G.C. Szego, "Economic and Logistic Considerations," *Proceedings: Seventeenth Annual Power Sources Conference*, 88. As one of his sources for this presentation, Szego cited *Power For the Future*, the 1960 analysis authored by the Harvard Business School graduate students.

Command's Engineer Research and Development Laboratories (ERDL) at Fort Belvoir, Virginia. Most of the work was concentrated in the latter two facilities: the ERDL dealt with large vehicular and semi-stationary powerplants of larger than one kilowatt, while the ECL concentrated on devices with output of less than a kilowatt for use with soldier-portable communications and surveillance devices.

It was the large hydrocarbon fuel cells that most fired the Army's imagination. Such devices, claimed the ERDL's B.C. Almaula, had the potential to replace all of the Army's internal combustion engines in both stationary and vehicular roles using common fuels.[115] Now, he asserted, all the research produced over the course of Project Lorraine was ready to be exploited. The ERDL would develop a five-kilowatt prototype fuel cell using hydrogen reformed from a liquid "hydrocarbon," which it expected to complete by early 1965. As for direct hydrocarbon oxidation in fuel cells, the Army considered that the fundamental principles had been proved and hoped that the doubts expressed by "various scientists and industrial managers" were now dispelled. With this key obstacle overcome, all that remained was to apply this knowledge, which was the responsibility of industry. As if to remind the conferees of the commercial rewards at stake, Almaula noted that the potential market for military hydrocarbon fuel cells was considerable.[116]

Despite this optimism, there were signs that all was not well in the terrestrial fuel cell program. The conference had opened to terse remarks from a researcher from the

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[115] B.C. Almaula, "High Power Ground Applications," in *Proceedings: Seventeenth Annual Power Sources Conference*, 83.

[116] Ibid., 83. One gains insight into the Army's hopes for power source technology in this period in its so-called "energy depot" concept. This was a small nuclear reactor that would serve as a mobile chemical factory. Parachuted into front line areas, the plant would either provide electricity directly or hydrogen and oxygen electrolyzed from local water sources. These gases could then power a fuel cell.

Army's Electronics Laboratory. David Linden indicated that a gap had opened between the presumed capabilities of the fuel cell as articulated by its champions and the abilities of the research and development community to realize these expectations. Despite the belief of the "sales and public relations people" that the fuel cell was just around the corner, "we engineers," noted Linden, were still having difficulty realizing even the more recently moderated claims.[117]

By summer, ARPA program managers were also having misgivings. In August, one began his report on the state of the electrochemical program with the observation that "not a single" catalytic or electrocatalytic reaction was fully understood. The lack of basic understanding was particularly galling in light of the apparent successes of hydrogen-fuelled aerospace fuel cells, which had much higher power outputs than hydrocarbon cells. Noting problems with low-temperature acidic fuel cells, particularly their need for platinum, the report's author hoped that perhaps a "neutral" electrolyte could be found that would avoid the shortcomings of the strong basic and acidic systems.[118] These were major criticisms, for Project Lorraine's primary purpose was, after all, to discover "physical principles." Nevertheless, the report endorsed the overall direction of the hydrocarbon research and Esso's work in particular. It observed that the oil company's experience in developing new catalysts for the methanol system over the previous two years was encouraging and recommended that it take on additional responsibilities experimenting with hydrocarbon systems.[119]

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[117] David Linden, "Introductory Remarks," in *Proceedings: Seventeenth Annual Power Sources Conference*, 80. The U.S. Army Signal Corps Research and Development Agency was redesignated as the U.S. Army Electronics Research and Development Agency and subsumed under the U.S. Army Electronics Command on 1 August, 1962.

[118] M.X. Polk, "Program Plan No. 148," 14 August 1963, Box 2, AO 247-Esso Research & Engineering, 1, National Archives and Records Administration II, College Park, MD.

What followed were non-linear work orders. Having ordered the rapid development of hardware, ARPA managers realized the resulting platinum-dependent acidic fuel cell technology was costly and unreliable. Now they let contracts to the Monsanto Research Corporation (MRC) for basic research to discover new and cheaper catalysts for use with liquid hydrocarbons.[120] In short, this was a renewal of the search for basic "physical principles." Monsanto researchers quickly confirmed that platinum was the most efficient of all catalysts and that substitutes were unlikely to be found. What was more, of the 15 catalysts chosen for investigation, 13 were active not for "organic hydrocarbons" but for hydrazine, an inorganic (non-carbonaceous) chemical chosen for its high reactivity.[121] Monsanto chemists hoped that a comparative study of hydrazine could yield insight into hydrocarbon oxidation. Though experience would demonstrate otherwise, hydrazine became an increasingly attractive fuel option for the Army after 1965 as the hydrocarbon project encountered further technical difficulties.

By the fall and early winter of 1963, new reports from Army and contract researchers and government energy agencies pointed to major physical and institutional obstacles in the terrestrial hydrocarbon fuel cell program. One of these, conducted by the California Research Corporation (CRC), invoked historical precedent to sweeten unpalatable news, a common tendency in the fuel cell research community. Because progress had occurred in early laboratory work, the CRC researchers wrote, this "leads one to believe appreciable further advances can be expected." They then undermined this and other key assumptions. One important problem was cooling, simple in a single fuel cell but much more difficult when many cells were clustered together in a battery or stack. Cooling was then no longer a two-dimensional but a three-dimensional problem, meaning that a way would have to be found to remove heat from the middle of the stack.[122] Reliance on platinum, however, remained the prime obstacle to widespread use of acid fuel cells. The CRC study indicated that schemes calling for outright replacement of internal combustion engines by acid fuel cells using even an extremely thin monatomic layer of platinum would require almost 2000 times the world's annual production of this metal.[123] A study commissioned by the Army's Harry Diamond Laboratories recommended that fuel cells should be considered only for special applications owing to the limited supply of platinum-group metals.[124]

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[119] Ibid.

[120] J.P. Ruina to Commanding General, U.S. Army Combat Developments Command, 18 February 1963, Box 4, AO 437-Monsanto Research Corporation, DA-44-009-AMC-202 (T) .

[121] John O. Smith et al., "First Quarterly Progress Report: Research to Improve Electrochemical Catalysts, 15 May, 1963 to 15 August 1963," 10 September 1963, Box 4, AO 437-Monsanto Research Corporation DA-44-009-AMC-202 (T), 1-2.

It soon became apparent within the fuel cell research and development community that General Electric had not considered the economics or the durability of the propane fuel cell announced to much fanfare in the spring. As an acidic system, the device rejected the carbon dioxide produced during fuel electro-oxidation but the reaction still corroded the electrodes, damaging lifetime and performance. Moreover, propane was far from the dirtiest fuel researchers hoped to use. General Electric conducted further tests throughout the summer and into the fall that further blurred distinctions between "basic" and "applied" research. The work of the "basic" Research Laboratory became more applied in nature. Researchers began testing "complete fuel cells" in order to understand and improve the performance of propane in an acid electrolyte system. Efforts to make more efficient use of platinum as a powder incorporated into the materials of various electrode configurations had a technological aspect to them.[125]

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[122] M.J. Schlatter et al., "Special Report No. 1: Appraisal of State of Development of Low Temperature Hydrocarbon-Oxygen (Or Air) Fuel Cells," 6 September 1963, Box 4, AO 566-Harry Diamond Laboratories, 1.

[123] Ibid., 1-2.

[124] Memorandum by Raymond H. Comyn, 8 November 1963, Box 4, AO 566-Harry Diamond Laboratories. Citing figures drafted by the U.S. Bureau of Mines, Comyn stated that the U.S. supply of palladium, the next most common platinoid metal after platinum itself, was sufficient to build only 30,000 automotive fuel cell powerplants per year. The U.S. imported almost its entire supply of platinum group metals. In 1962, it consumed 866,459 Troy ounces, the lion's share of annual world production of a little over 1.3 million ounces, but produced only 28,742 ounces.

Similarly, materials testing, a study of basic "physical principles," now became an additional preoccupation of the "applied" DECO laboratory. Such tests revealed that not all of the electrodes developed by the Research Laboratory were sufficiently robust to withstand prolonged contact with acid. The challenge was to seek combinations of cheap metals that were reactive as well as corrosion-resistant. Experiments with a variety of materials in concentrated phosphoric acid at 150°C demonstrated the difficulty of meeting these conflicting requirements: even electrodes made from noble metals like platinum and gold slowly disintegrated in the hot corrosive mixture over time. Other materials such as molybdenum, tungsten and palladium-nickel alloy (platinum black) experienced severe degradation. Once electrodes were under load in phosphoric acid, a complex mixture of different chemical substances was produced within fuel cells that made a quick analysis of the precise composition, and further experimentation, very difficult.[126]

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[125] General Electric, "Saturated Hydrocarbon Fuel Cell Program, Quarterly Letter Report Number 4, July 1 1963-September 31 1963," undated, Box 2, AO 247-General Electric, 2.

Meanwhile, DECO's test division continued to suffer from the effects of the construction delay resulting from the funding cut the previous September. By late October 1963, no test stations were fully operational. Only two had been partially completed, although five were projected to be ready by November. Work in this sector proceeded at a low ebb. Only a single cell was undergoing durability testing and the longest lifetime demonstrated thus far had been a propane cell that lasted for 300 hours. By then, experiments were already proceeding with more common liquid fuels like octane.[127] As with previous fuel cell programs, engineers tended to focus first on current density and only afterwards consider durability. However, the same problems of corrosion and materials degradation that destroyed the test propane cell after 300 hours remained for the moment unaddressed.

Difficulties in the hydrocarbon fuel cell program were noted in a sweeping survey of the federal government's energy research and development efforts. Initiated as a Kennedy administration executive order in late 1963, the comprehensive year-long cabinet-level Interdepartmental Energy Study (IES) outlined the uncertain utility and contingent nature of energy research and development in general and the hydrocarbon fuel cell project in particular. Planning for such programs, it indicated, was "inherently complex and imperfectly understood."[128] The key problem, the IES believed, was organizational. Energy research and development was in a state of disarray. Given the wide variety of non-constant variables including natural resources, science, technology, economics, sociology and politics, the problem was likened to solving a "highly non-linear mathematical problem." Planning was reduced to a scientific formula and was, as a result, highly speculative.[129] The uncertainty was compounded by the decentralized state of federal energy research and development. A wide variety of military and civilian agencies carried out their own energy programs. Where fuel cells were concerned, the authors of the IES shared assumptions held by ARPA managers. They believed that valuable information relevant to terrestrial designs would be obtained from aerospace fuel cells. On the other hand, the IES panel conceded that such experience might equally prove relevant only for aerospace designs, given their short lifetimes and requirement for pure hydrogen and oxygen.[130]

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[126] Ibid., 6.

[127] Ibid., 8.

[128] *Energy Research and Development and National Progress*, v. The federal agencies involved in the study included the Office of Science and Technology, the Bureau of the Budget, the Office of Emergency Planning, the Departments of Defense, Interior, Commerce, Labor, State, and Health, Education and Welfare, the Atomic Energy Commission, the Federal Power Commission, the National Science Foundation and the National Aeronautics and Space Administration.

Nevertheless, the IES indicated that all fuel cells including hydrogen-oxygen designs had the potential to consume hydrocarbons if cost-effective reforming technologies could be developed. The real problem was a lack of knowledge. The report noted that while preliminary tests seemed to indicate that fuel cells could yield incredible efficiencies of up to 90 per cent and that long-term invariant operation was possible, little was known of the lifetime and reliability of any of the designs currently under study, let alone the challenges of scaling-up small laboratory cells into large multi-celled stacks. The dearth of information made estimates of future progress highly speculative. These problems, the IES suggested, stemmed from poor planning. Without a federal energy superagency, efforts were uncoordinated and unbalanced. Prestigious fields such as physics and aerospace attracted a preponderance of workers while others were crippled by a shortage of skilled researchers, a problem particularly acute in the fuel cell field. The study concluded that such problems would greatly complicate any attempt to intensify the fuel cell program on a national level.[131]

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[129] Ibid., xviii.

[130] This position almost certainly reflects Ernst Cohn's views. He sat on the IES committee reviewing fuel cells and framed matters in virtually the same terms as in an internal NASA report completed for the survey; Cohn, "Interdepartmental Energy Study: Chemical and Biochemical Fuel Cells," 19 August 1963, Record Number 13761: Propulsion: Auxiliary Power: Fuel Cells, 1961-1999, 13, NASA Headquarters Archive.

Indirectly, the IES summed up the shortcomings of the terrestrial fuel cell program. As the prospects for an affordable and efficient hydrocarbon fuel cell faded by late 1963, industry's rationale for participation in Project Lorraine ended. Many firms abandoned fuel cell research altogether. The specialized roles that had always hovered in the background as a secondary goal should the hydrocarbon fuel cell effort fail now became increasingly politically important to ARPA. It began a new campaign to justify the non-economic advantages of terrestrial fuel cells, invoking new standards of desirability. Charles F. Yost, the agency's director for materials sciences, claimed the "downward trend" in industry support did not necessarily reflect poorly on the utility of fuel cells, for they were still suitable for specialized roles in the armed services in conditions where long life was not essential and cool, quiet operation was important. The loss of industrial support was, however, a serious blow, as the Department of Defense relied on private companies to underwrite a major portion of the research program, amounting to several million dollars, perform most of the engineering and, it was hoped, produce fuel cell stacks in quantity. With companies now pulling out, observed Yost, a military terrestrial hydrocarbon fuel cell program would rely solely on government support.[132]

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[131] *Energy Research and Development and National Progress*, 302-303.

Interestingly, an initial draft of the Interdepartmental Energy Study had recommended spending an additional $3 to $4 million on the hydrocarbon project, some of which was to fund an electrochemical training program, and postponing the methanol fuel cell in favor of increased research on hydrocarbon oxidation. This was received coolly in some ARPA quarters. The Materials Sciences Office regarded the training program with ambivalence. It did not dispute that there was a shortage of electrochemists, but suggested that with the solution of low-temperature hydrocarbon oxidation lying eight to ten years in the future, an immediate effort to produce more workers was superfluous. Conversely, the methanol fuel cell was the only fuel cell technology that was "essentially at hand" and could "serve a useful purpose."[133]

The federal study illuminated all the contradictions in ARPA's policy of linear research of basic physical principles. The agency's original plan had been to support basic research in electrochemical conversion of hydrocarbons that would at some point inform technology demonstrations managed by the armed services and executed by industry. Instead, difficulties on the "basic" side inspired a rush to develop simpler technologies such as the methanol fuel cell and the hydrocarbon reformer until direct hydrocarbon oxidation could be perfected. Yet these programs, too, had developed non-linear dynamics. As Yost noted, "basic" problems had arisen in the "applied" side of the program. The resultant mass of inconclusive research and undeveloped technology concepts was unattractive to both industry and the military.[134] Despite this, ARPA was committed to moving from research to development. In the fall of 1963, the agency prepared to wind down Project Lorraine; it decided to end most of the basic programs and support the technology projects of the two big contactors for two more years in an effort to make them acceptable to the military.[135] ARPA's tactic of lowering expectations and developing interim hardware as a means of sustaining political support would be emulated by the Army as it embarked on its fuel cell technology program in 1965.

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[132] Memorandum by Yost, 12 September 1963, Box 4, Project Lorraine-Energy Conversion, 2, National Archives and Records Administration II, College Park, MD.

[133] Huth, "Comments on the Interdepartmental Energy Study," 8 October 1963, Box 4, Project Lorraine-Energy Conversion, 2-4. Huth claimed that in 1963, there were only four academicians in the U.S. specializing in electrode phenomena specifically relating to fuel cells, with a combined output of under 40 students per year: Yeager (Western Reserve), Bockris (University of Pennsylvania), Tobias (University of California), and Delahay (Louisiana State University). The conclusions in the published version of the Interdepartmental Energy Study (IES) differed significantly from the draft report reviewed by ARPA managers in the fall and appeared to incorporate the agency's views on the hydrocarbon project. Although the published study noted that the shortage of electrochemical workers threatened the long-term viability of the program, it did not contain any of the proposals cited in the draft, including the funding increase for electrochemical training or for fuel cell research in general. Also, the published report seemed to reverse the draft's assessment of the methanol cell, referring to it instead as the most advanced project involving oxygenated hydrocarbons. These revisions reflected the respective views of Huth and NASA's Cohn, both of whom had sat on the IES fuel cell panel.

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[134] John H. Huth, "Status Report-Project Lorraine," 31 October 1963, Box 4, Project Lorraine-Energy Conversion, 3.

[135] Charles F. Yost to R.L. Sproull, "Phaseout of the Energy Conversion Program (Project Lorraine)," 1 November 1963, Box 4, Project Lorraine-Energy Conversion, 3.

3 - Crisis of Expectation: Moving from Research to Development in the Terrestrial Fuel Cell Program

The sociologist Bruce Podobnik has observed that the development of energy and power technologies has historically been driven by a mixture of economic, political and cultural factors rather than by material "demand."[1] A similar dynamic informed the Department of Defense's hydrocarbon fuel cell program. As we saw in Chapter Two, Project Lorraine was begun for technopolitical reasons quite apart from "necessity." Similarly, ARPA's decision in 1962 to shift emphasis from the dedicated search for physical principles to the construction of prototype hardware occurred not because the basic physical and engineering principles of fuel cells had been mastered but largely for political and ideological reasons. In turn, the transfer of embryonic fuel cell technology systems from ARPA to the U.S. Army presented researchers with a range of new problems. As they began to build full-scale prototypes and as ARPA ended its support of basic research, expectations for practical fuel cell technology mounted. Engineers soon discovered, however, that the search for physical principles, assumed by ARPA to have concluded in late 1963, continued during hardware development for the Army.

This chapter will explore the technopolitical consequences of the Department of Defense's transition from "research" to "development" in the terrestrial fuel cell program. It will focus on how phasing out basic research between 1963 and 1965 shaped the material practices of fuel cell laboratories and how this in turn informed the kinds of technologies Army and industry workers chose to develop between 1965 and 1972. While the demonstrative power of prospective testing had helped forge a coalition between ARPA, industry and the Army, the development of larger and more complicated fuel cells, and the movement of the locus of testing from industrial to Army laboratories, presented ARPA with a quandary. As scaled-up laboratory fuel cells succumbed to a variety of problems, industry and the Army were increasingly reluctant to take responsibility for developing them into full-scale prototypes. While ARPA's involvement in hydrocarbon fuel cells had been predicated partly as an effort to help it retain its relevance and identity as a federal bureau of research and development after relinquishing its space programs to NASA, the agency, after three years of inconclusive research, had come to view the project as a burden. Though ARPA was by then eager to end its involvement, some corporations still under contract as part of Project Lorraine continued to seek funding for research. This was in fact "engineering research," the long-term testing of full-size fuel cells under realistic operating conditions, a social practice that represented as much a renewed search for physical principles as it did a transition from "research" to "development."

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[1] Bruce Podobnik, *Global Energy Shifts: Fostering Sustainability In a Turbulent Age* (Philadelphia: Temple University Press, 2006), 63.

Yet the long-term and inconclusive nature of engineering research meant that the political basis for this practice was weak. ARPA's managerial-organizational doctrine did not recognize or budget for it. Engineering research was a task the Department of Defense instead reserved for the Army. As Donald MacKenzie has noted, inferring from test performance to actual use is limited by the time and resources that can be devoted to testing.[2] As the Army's energies were absorbed by the war in Vietnam in the late 1960s, its laboratories were increasingly ill-equipped and philosophically ill-disposed to engage in the protracted work of making fuel cells durable and long-lived.

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[2] Donald MacKenzie, "From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy," in *The Uses of Experiment: Studies in the Natural Sciences*, eds. David Gooding, Trevor Pinch and Simon Schaffer (Cambridge: Cambridge University Press, 1989), 414.

When the Army finally deployed fuel cell systems in field trials in the early 1970s, they met none of the previous assumptions of performance and cost. In view of the resulting gap between expectations for a miracle battery and the tedious and unrewarding work of engineering research, the Department of Defense began to reconsider its commitment to fuel cell technology.

Engineering Failure: ARPA, General Electric and the Technopolitics of "Phase-out" Research and Development

ARPA's decision in 1963 to end basic research and move to hardware development as it terminated Project Lorraine had important political consequences for its internal affairs, for its relations with the Institute for Defense Analyses and for the Army's fuel cell technology program. As industry and the Army attempted to move from "research" to "development" and produce prototype fuel cells from the mass of raw research, the search for "physical principles" did not end. On the contrary, each progressively more advanced stage of technology development introduced novel chemical and electrochemical phenomena, necessitating the intensification, not diminution, of fundamental scientific inquiry, and appropriate commitments of resources. With such resources no longer available and with the Pentagon demanding prototype fuel cells for field trials in Vietnam, the Army laboratories emulated processes of simplification developed during Project Lorraine. They sought interim fuel hardware that could provide useful service and buy time while researchers struggled to master the direct hydrocarbon fuel cell.

ARPA's decision to end basic research was not without critics. General Electric felt that more, not less, research was needed to determine how some of the scaled-up hydrocarbon fuel cell systems behaved over time. Officials in ARPA's Materials

Sciences Office agreed. Though John Huth opposed plans to bolster electrochemical training, he had warned that ending basic research would "inadvertently bypass significant factors," leading to a techno-scientific dead end.[3] This did not bode well for the contractors' programs, which were "essentially intuitive" in nature at that point, as Charles F. Yost noted.[4]

ARPA managers also demonstrated a new willingness to criticize the role the Institute for Defense Analyses had played in shaping the conduct of carbonaceous fuel cell research and development in Project Lorraine. Huth attacked one report authored by Robert Hamilton and G.C. Szego in late 1963 as a mix of "widely collected data" and opinion with forecasted end-uses of fuel cells, creating a misleading impression as to what was actually possible given existing and projected states of the art.[5] The IDA analysts cited extremely high power densities obtained in hydrocarbon and methanol fuel cells as evidence of progress but did not account for "parasitic" demand, the power that various accessory systems including pumps, fans and reformers drew from overall output.[6]

This questioning of the IDA occurred during a period of transition in ARPA's leadership and dissatisfaction within the Department of Defense with the results of the national materials sciences program. In September 1963, J.P. Ruina stepped down as ARPA director and was replaced by Robert L. Sproull, a physicist and the former chief of Cornell's ARPA-sponsored Interdisciplinary Materials Sciences Laboratory.

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[3] John H. Huth "Status Report-Project Lorraine," 31 October 1963, Box 4, Project Lorraine-Energy Conversion, 3, National Archives and Records Administration II, College Park, MD.

[4] Charles F. Yost to R.L Sproull, 12 September 1963, Box 4, Project Lorraine-Energy Conversion, 2.

[5] John H. Huth, "Comments on IDA Report R-103 by R. Hamilton and G. Szego," 2 March 1964, Box 4, Project Lorraine-Energy Conversion, 1.

[6] Ibid., 3.

Sproull believed the university materials programs were taking too long to produce technology and felt similarly about Project Lorraine.[7] In March 1964, he immediately took the Materials Sciences Office's complaints against the IDA to the Office of the Director of Defense Research & Engineering, claiming that the agency had found numerous "inconsistencies, inaccuracies and duplications" in Hamilton and Szego's report and requested that it be thoroughly revised and resubmitted.[8] While this critique was directed at a specific paper, it could well have applied to previous IDA estimates, highlighting the institute's bias towards technology development at the expense of basic research and its role in ARPA's adoption of this policy in Project Lorraine. Sproull, like his predecessor Ruina, perceived the program in "technological" terms. He concentrated on improving components like electrocatalysts and electrodes, as well as waste removal systems, making them more compact, durable and less expensive. As Sproull observed in March 1964, the fuel cell programs were expected to be ready for adoption by the armed service laboratories for study and prototype development by 1965. Sproull assumed that the services could now configure the technology according to their requirements, relieving ARPA of its responsibilities.[9]

Bridging the gap between the "basic" and "applied" phases of technology development, however, proved difficult. Despite the sweeping claims for the hydrocarbon fuel cell made by the Army's Engineer Research and Development Laboratory representative at the Power Sources Conference of spring 1963, lack of resources was impeding the transition from "research" to "development." Sproull reflected that ARPA's budget for energy conversion was so small that the agency had little chance of making a major contribution and that the real developments in the field would be made in industry and the "civilian agencies," presumably meaning NASA.[10] This position overlooked the fact that ARPA was then the sole sponsor of terrestrial fuel cells of the kind suitable for the civilian market. Sproull nevertheless appealed to the Secretary of the Army to bolster the Army's research and development budget to account for the loss of $2 million when ARPA's commitment expired at the end of Fiscal Year 1965 in September 1965.[11]

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[7] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974* (Washington, D.C.: ARPA, 1975), VI-46-48.

[8] Sproull to Assistant Director of Defense Research and Engineering, 4 March 1964, Box 4, Project Lorraine-Energy Conversion.

[9] Sproull to Secretary of the Army, 9 March 1964, Box 4, Project Lorraine-Energy Conversion, 1-2.

The spectacle of the ARPA chief lobbying the Army to undertake activities that had hitherto been the responsibility of the Department of Defense likely did not inspire confidence in the terrestrial fuel cell program among Army leaders. This came as researchers prepared to more intensively test laboratory cells and cell stacks. General Electric's Research Laboratory realized the situation was far more complex than it originally believed. It was less optimistic that the problems facing the terrestrial hydrocarbon fuel cell program could be resolved than it had been one year earlier. The company's first quarterly report of 1964 depicted a bleak picture of the laboratory floor. For the first time, the report did not summarize the activities of the Schenectady laboratory, only the Lynn facility. Efforts there had been greatly diminished. The staff had been reduced from five to two principal investigators and the laboratory had dropped all other activities save life testing.[12] Even here, work was cut back. All ten testing stations had finally been completed, but only three hydrocarbon half-cells were being tested, all of which were fuel anodes employing platinum catalysts.[13]

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[10] Richard J. Barber Associates, Inc., *The Advanced Research Projects Agency, 1958-1974*, VI-60.

[11] Ibid., 1. There appears to have been some uncertainty among ARPA managers over precisely what the phase-out and accelerated component work would accomplish and whether the subsequent funding would continue to come directly from the Department of Defence or from the Army's research and development budget. In his 9 March memorandum, Sproull had originally requested that the program be continued in its present form, concluding that "practical, low-temperature air-breathing fuel cells of considerable value to the Army can ultimately be developed." This sentence was subsequently removed in a revised version of the memo and replaced with a paragraph calling simply for an increase in the Army's research and development budget.

Testing indicated that cells using the heavier hydrocarbons experienced slow, steady decay in output over time. The precise cause was still unknown, although there was speculation that a waste produced during the oxidation of the hydrocarbon was coating the electrode surface. Because testing had been underway for only a short period of time, the results were inconclusive. The report's authors cautioned against drawing conclusions from these experiments because they had been small in number and in no way represented the characteristics of electrodes in general.[14]

By this point, the Research Laboratory personnel firmly believed that basic and applied science in fuel cell electrochemistry were seamless. They were also aware of the problems created by simplification. A paper written in March 1964 revealed their techno-scientific understanding of the nature of their work and the limited progress made thus far. The team noted that the investigation of electrode structure had not yet achieved a scientific basis. It wanted a massive survey of the field and extensive experiments in order to understand the relationship between the physical structure of electrodes and current density in liquid electrolyte systems. Part of the difficulty was that in developing a theory of materials-electrode interaction, researchers had used simple laboratory electrodes with structures and operating dynamics quite unlike commercial electrodes. Because hydrocarbons yielded reactant products, they placed much more stress on electrodes than hydrogen and oxygen reactants. While simple models could help in conceptualizing this relationship, the team noted, their value was mainly qualitative, given the complexity and dynamism of these processes. Future work, the team stated, would emphasize analyses of full fuel cells, hinting at the hazards of drawing conclusions from half-cells, then a common practice in fuel cell research communities.[15] This was a far cry from the Research Laboratory team's unalloyed optimism of 1963. In the summer of 1964, one year after he had congratulated Liebhafsky and General Electric for their "breakthrough," Bacon wrote him once more. This time, the tone was consolatory and philosophic: "Are we getting nearer to a really practical direct hydrocarbon fuel cell or is it still a long way off? I wish I knew the answer to this question!"[16]

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[12] Paul Chludzinski and Max Gloor, "Quarterly Letter Report Number 5, January 1, 1964-March 31, 1964," undated, Box 2, AO 247-General Electric, 1. In 1963, DECO had six staff, including five principal investigators (P.V. Popat, Paul Chludzinski, D.I. Macdonald, G.F. Wheeler and H.J. Young). E.A. Oster provided technical direction. In 1964, only Chludzinski and Gloor remained.
[13] Ibid., 3.
[14] Ibid., 1.

In March 1964, General Electric attempted to obtain more government support for basic research. Its power generation representative, J.W. Babcock, approached the Army's Engineer Research and Development Laboratory seeking to extend its contract between 12 and 18 months. Though progress had been "gratifyingly rapid" since fall 1962, when General Electric had first oxidized a saturated hydrocarbon in a phosphoric acid electrolyte-platinum catalyst fuel cell, and though current densities had improved by an order of magnitude, they were, Babcock noted, still too low to justify "engineering design." Developing the basic technology necessary to help design direct hydrocarbon fuel cells entailed a research program of "considerable scope and inordinate difficulty."[17]

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[15] H.A. Liebhafsky, E.J. Cairns, W.T. Grubb and L.W. Niedrach, "Current Density and Electrode Structure in Fuel Cells," in *Fuel Cell Systems: Symposia Sponsored by the Division of Fuel Chemistry at the 145th and 146th Meetings of the American Chemical Society, New York, N.Y., Sept. 12-13, 1963, Philadelphia, Pa., April 6-7, 1964* (Washington, D.C.: American Chemical Society, 1965), 117, 125. A complete cell comprised one negative (anode) and one positive (cathode) electrode. A half-cell consisted only of one or the other.

[16] Bacon to Liebhafsky, 10 June 1964, Bacon TS, Section G, Correspondence, Fuel Cell Correspondence, G.133.

What was needed now, Babcock stated, was further study of the "nature of electrocatalytic processes" and "chemical engineering parameters," as well as life testing, a "critical part of the program." In a program where funding had been based almost entirely on expectations of a breakthrough, promises of future success carried less weight at this stage. Now, all General Electric could offer was little more than a better understanding of the electrochemical labyrinth that was the hydrocarbon fuel cell. Ironically, eighteen months earlier, Babcock had spoken as if all the fundamental problems of electrochemical energy conversion had been solved, citing favourable estimates of *production* costs to the IDA's George Szego. In turn, Szego had promoted the idea that the day of the hydrocarbon fuel cell had arrived, likely influencing ARPA's decision to shift the emphasis in Project Lorraine away from basic research towards technology development. Now, Babcock was asking the Army for more money for basic as well as applied research.

The ERDL in turn looked to ARPA for support. In a letter to Sproull, Charles F. Cashell, acting for Oscar P. Cleaver, head of the laboratory's electrical department, noted the additional efforts necessary to bring the program to fruition. Importantly, the ERDL shared with General Electric a techno-scientific understanding of the nature of program that was at odds with ARPA's research and development philosophy. Cashell referred to the necessity of developing "fundamental fuel cell technology" as the bridge to determining whether it was feasible to proceed with larger and more sophisticated devices. He warned that such an effort might not bear fruit and in fact succeed in proving only that it was not feasible to develop hydrocarbon fuel cells. Cashell also hastened to underline just what was at stake, claiming the program was vital to maintaining the mobility of the "Armed Forces."[18] He probably exaggerated the breadth and depth of a military constituency for a hydrocarbon fuel cell. The interest of the Air Force and Navy in fuel cells was marginal: like NASA, they focused on hydrogen-oxygen types for special applications where high performance outweighed cost.[19]

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[17] J.W. Babcock to O.P. Cleaver, 16 March 1964, Box 2, AO 247-General Electric, I, National Archives and Records Administration II, College Park, MD.

In April, Assistant Army Secretary Willis M. Hawkins wrote Sproull. He indicated that while the Army would consider ARPA's request to support basic and applied research, it was doubtful that $2 million could be supplied given recent reductions in the service's overall research, development, testing and evaluation budget. Hawkins suggested that combined Army-ARPA spending of $3.9 million on fuel cells in Fiscal Year 1964 was sufficient, referring the request for $2 million instead to the Office of the Secretary of Defense for review.[20]

As ARPA and the Army haggled over who would pay for hydrocarbon fuel cell research, news from the space program, long a yardstick of progress in the field and a source of hope for managers of the terrestrial fuel cell program, gave further cause for gloom. Problems with the Gemini and Apollo hydrogen-oxygen fuel cell programs, warned Huth, should temper any "overoptimism" in the progress of the hydrocarbon project.[21] The fact that such difficulties had been encountered with ostensibly simpler hydrogen-oxygen fuel cell technology did not auger well for the fortunes of the hydrocarbon project.

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[18] Charles F. Cashell to R.L. Sproull, 18 March 1964, Box 2, AO 247-General Electric, 1.
[19] Gerald E. Starkey, "Fuel Cells in Aerospace," in *Proceedings: Seventeenth Annual Power Sources Conferences, 21-23 May 1963* (Red Bank, NJ: PSC Publications Committee, 1963), 84-85.
[20] Hawkins to Sproull, 13 April 1964, Box 4, Project Lorraine-Energy Conversion, National Archives and Records Administration II, College Park, MD.

Liebhafsky was as keenly aware of the technopolitical difficulties created by simplification and the linear conduct of hydrocarbon fuel cell work as the physical obstacles posed by the technology. He was not optimistic that he would have the opportunity to solve the problems posed by scaled-up fuel cells. As he confided to Bacon in the summer of 1965, General Electric's terrestrial hydrocarbon fuel cell program was vulnerable because it relied almost entirely on government support. Continued aid was contingent on the development of "useful" hardware within two to three years, but he did not believe that this was possible. With prospects bleak, Liebhafsky suspected that his best researchers would soon begin to leave for greener pastures. His bitterest complaint, however, was reserved for the culture of corporate secrecy in fuel cell development, singling out Pratt & Whitney. He believed that unless the industrial laboratories started to cooperate, the terrestrial fuel cell program threatened to "flop."[22]

In a 1966 paper, Liebhafsky noted the imprecision of the conventional identification of the individual fuel cell as the province of "research" and the fuel cell battery as an "engineering assignment." Strictly speaking, he stated, research continued during the engineering phase. There was sufficient theoretical knowledge of hydrogen-oxygen cells to begin “engineering,” defined as the selection and arrangement of materials in fuel cell stacks that would result in uniform chemical operations. The same could not be said of the hydrocarbon fuel cell.[23] Yet while a hydrogen-oxygen fuel cell represented a tolerable “engineering” challenge, this was meaningless to the sponsors of the terrestrial hydrocarbon fuel cell research program. As ARPA ended its support of basic research in 1965, General Electric failed to deliver reliable individual direct hydrocarbon fuel cells, let alone a working stack. Time had run out. This left Esso’s methanol fuel cell as one of two interim technologies produced through Project Lorraine for evaluation by the Army.

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[21] John H. Huth, "Renewal of Fuel-Cell Contracts with GE & Esso During FY 1965," 6 May 1964, Box 2, AO 247-General Electric, I.
[22] Notes on meeting with H.A. Liebhafsky by F.T. Bacon, 13 June 1965, Bacon MS, Section G, Correspondence, Fuel Cell Correspondence, G.135.

Scaling-Up Complexity, Downgrading Expectations: Esso’s Methanol Fuel Cell

The course of Esso Research and Engineering’s (R&E) technology development effort in the final months of Project Lorraine illustrates how the arbitration of design was determined where the politics of research and development met the material realities of scaled-up fuel cells. In 1963, the company’s chief fuel cell researcher believed results obtained on laboratory test units could be applicable to larger units.[24] Over the course of the year, however, Esso engineers discovered that complete direct methanol fuel cells, much less large stacks, behaved fundamentally differently than half-cells.

A key problem was platinum’s high reactivity, the very quality that made it so desirable as a catalyst. The Esso fuel cell was a direct system, which injected methanol into the sulfuric acid electrolyte. When this occurred, the fuel came in contact not only with the fuel electrode (anode) but the oxygen electrode (cathode) as well. The platinum-laced cathode oxidized some of the methanol before it could be consumed at the anode, greatly reducing efficiency through fuel wastage and increased cathodic overpotential, the fraction of energy produced by the reaction necessary to drive the overall reaction. Further, cathodic oxidation produced large amounts of carbon dioxide that physically displaced the electrolyte. As there was no physical means of preventing this, Esso engineers tried to reduce the amount of methanol dissolved in the electrolyte.[25]

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[23] H.A. Liebhafsky, “Fuel Cells and Fuel Batteries: An Engineering View,” *IEEE Spectrum* (December 1966): 53.

[24] C.E. Heath, “The Methanol-Air Fuel Cell,” in *Proceedings: Seventeenth Annual Power Sources Conference, 21-23 May 1963* (Red Bank, NJ: PSC Publications Committee, 1963), 97.

By the summer of 1964, Esso wanted to be rid of the methanol program for reasons that had little to do with these technical issues but rather stemmed from the company's original commercial motivations and expectations in taking up fuel cell research. In a draft proposal completed in July 1964 calling for the continuation of government-funded research, Esso R&E's Research Division reversed the priorities that had been set for it by ARPA in August 1963. This was a belated reaction to ARPA's decision to make Esso responsible for developing the methanol fuel cell as an interim technology until the enigma of direct hydrocarbon oxidation had been solved. Should the program be extended throughout 1965, Esso held, the main goal should be to conduct feasibility studies of a genuine hydrocarbon-air fuel cell "capable of widespread military application."[26]

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[25] Heath, "Methanol Fuel Cells," in *Proceedings: Eighteenth Annual Power Sources Conference, 19-21 May 1964* (Red Bank, NJ: PSC Publications Committee, 1964), 34.

[26] Esso Research and Engineering Company, Process Research Division, "Proposal for the Continuation of Government Contract Research on Fuel Cells; Program Period-Calendar Year 1965," 24 July 1964, Box 2, AO 247-Esso Research and Engineering Company, 1, National Archives and Records Administration II, College Park, MD.

In this report, Esso reminded ARPA that the whole purpose of developing a hydrocarbon fuel cell was to reduce the burden of fuel logistics. Conceiving the technology as a universal energy converter, ARPA and Army planners hoped such a fuel cell could consume fuels common to the military supply chain, or that were at least derived from them. This plan envisioned substituting fuel cells for other power sources in large numbers, a situation that, on paper, would satisfy Esso's interest in selling large amounts of fuel cell fuel. Though applications could be found for the methanol fuel cell, it had been apparent to ARPA, Army and industry managers for some time that these would be niche roles where the importance of silent, cool operation was emphasized.[27] The volume of fuel a handful of methanol cells would consume in such roles was negligible. For Esso, such a technology was commercially marginal.

Nevertheless, the Esso R&E laboratory prepared the methanol fuel cell for further development by the Army's Electronics Components Laboratory (ECL).[28] The imperatives of the "phase-out," not the needs of the end-user, would determine the final stages of Project Lorraine. With the Department of Defense deciding to conclude "basic" research, the approach to technology development remained as linear as ever. Esso R&E would complete a device that it and the Army's ECL presumed would be used with radios or perhaps radars. But it would not extensively test the device in such applications because its obligations in Project Lorraine would end with the program's termination. Consequently, Esso tested individual components before turning fully-integrated, though untested, hardware over to the Army. The possibility that tests in the laboratory and in the field might imply completely different electrochemical phenomena did not seem to occur to any of the concerned parties.

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[27] Ibid., 1.

[28] Ibid., 43. Esso's priorities could be gauged from the resources it proposed to allocate to its two fuel cell projects. The hydrocarbon oxidation program merited 17.1 professional and 13.4 non-professional staff. On the other hand, the methanol project was to be allocated 6.5 and 8.9 staff in these respective categories.

While Esso researchers imagined that the methanol fuel cell might be used with a "manpacked" battery-operated radio, they could not guarantee that they would be able to make it light enough to be useful in this role. They considered the chances of developing a heavy methanol fuel cell "excellent," though only "50 per cent" for a lighter design.[29] Weight was crucial because it meant the difference between a device that could be carried by the individual soldier relatively easily and one that could not. That, in turn, dictated whether or not such a fuel cell was superior to a conventional battery. If the Esso system was too heavy for "manpacking," the only other application was in a stationary role, one that brought no logistical advantages. Since Esso could not predict the final weight of the device it was developing, it could only speculate on the applications to which the device might be put.

Another key problem was the durability of full-sized prototypes. Through the remainder of 1964 and into 1965, Esso engineers worked to replicate on "multi-cells" the high performance recorded on individual cells, a key requirement of all fuel cell operating systems being long-term chemical invariance with as little recourse to control equipment as possible. This was especially true of the methanol fuel cell as compared with hydrogen-oxygen designs, as Esso researchers noted, because of the additional "process complexity" demanded by the direct fuel design. The electrolyte had to be circulated and methanol added in response to the load demand of the appliance the fuel cell powered in such a way as to maintain a chemical equilibrium, a task complicated by the tendency of the platinum-laced cathode to prematurely oxidize methanol.[30]

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[29] Ibid., 30.

Researchers soon realized that operating stacks of cells was far more challenging than individual cells. Esso's 16-cell stack was wired in series, meaning unlike terminals of each successive cell were connected together (cathode to anode), as opposed to a parallel connection, in which the like terminals were linked (anode to anode, cathode to cathode). As General Electric's Liebhafsky observed, series connections produced higher voltages and were more efficient than parallel linkages.[31] This was an important design consideration for the Esso technology because carbonaceous fuels produced lower voltages and were less efficient in fuel cells than hydrogen. Since many electronic appliances required high voltages, this was a serious handicap. Wiring stacks of carbonaceous fuel cells in series helped compensate for this shortcoming.

But series-linked fuel cells were more prone to failure than those connected in parallel because they were only as robust as the least reliable cell. If the supply of gases to a series-linked cell in a fuel cell stack was not uniform and hydrogen and oxygen starvation occurred, there was a possibility that undesirable reactions could occur at its electrodes. In certain situations, a weak cell could be "driven" by adjacent cells, reversing the charge of its electrodes and turning it into an electrolysis cell. Instead of being drained by the circulation system, water normally produced at the cathode might be captured and electrolyzed, producing oxygen at the anode side and hydrogen at the cathode side and bringing about the failure of the entire stack.[32] What was more, ensuring a uniform distribution of reactants to all cells in a multi-cell array was difficult, requiring painstakingly-machined gas distribution passages.[33]

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[30] Barry L. Tarmy, "Methanol Fuel Cell Battery," in *Proceedings: Nineteenth Power Sources Conference, 18-20 May 1965* (Red Bank, NJ: PSC Publications Committee, 1965), 41-42.
[31] Liebhafsky, "Fuel Cells and Fuel Batteries: An Engineering View," 54.

Despite these challenges, Esso was confident that the methanol fuel cell battery had displayed "realistic performance levels under reasonable operating conditions."[34] Yet the company's test regimen had hardly replicated such conditions if they referred to circumstances likely to be encountered in the field. As of spring 1965, Esso had reserved the most rigorous tests for half and individual single cells, which lasted up to 6000 hours. Multi-cell assemblies, on the other hand, had been tested only to 200 hours.[35] Researchers did not state whether this was long enough to determine if the variations in the operating patterns of individuals cell posed a serious long-term durability problem for the complete array. Nor does it appear that Esso tested the fuel cell with an actual application. Nevertheless, the Army's Electronics Components Laboratory (ECL) took delivery of Esso's experimental 16-cell 100-watt methanol fuel cell in January 1965. The ECL declared the technology a major milestone, the first fuel cell stack to oxidize methanol directly without relying on external reforming.[36]

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[32] Ibid., 54.

[33] Barry L. Tarmy, "Methanol Fuel Cell Battery," in *Proceedings: Nineteenth Power Sources Conference, 18-20 May 1965*, 41-42.

[34] Ibid., 43.

[35] Ibid., 43.

[36] Historical Branch Headquarters, *Annual Historical Summary of U.S. Army Electronics Command, 1 July, 1964-30 June, 1965*, 1 March 1967, Historical Research Collection, Annual Historical Data, Annual Historical Summary, 1 July, 1964-30 June, 1965, 1012, Communications and Electronics Command Historical Research Collection, Communications-Electronics Lifecycle Management Command Historical Office, Fort Monmouth, New Jersey (hereafter cited as CECOM Historical Research Collection).

Closing the Books on Project Lorraine

The methanol fuel cell was an object lesson of the life cycle of a technology in search of a role, one shaped more by technopolitical requirements than by practical considerations. Work had persisted because the IDA and ARPA believed that the methanol cell could shed insight into the far more complex chemistry of the hydrocarbon fuel cell. It is doubtful, however, that the device provided much insight into the latter problem owing to the fact that methanol was a relatively simple chemical and was electro-oxidized with relative ease compared to some of the hydrocarbons the Army wanted to use. Neither could the methanol fuel cell be considered a practicable technological shortcut, for, like all low-temperature direct hydrocarbon systems employing platinum catalysts, it was susceptible to side reactions.

The decision of IDA and ARPA to develop the methanol fuel cell can be seen as hedge calculated to sustain support among a variety of constituencies in a complex program spread widely across a defense research and development community in which firm knowledge of the full range of electrochemical issues at play was in short supply. Through the construction of hardware, industrial contractors and IDA and ARPA program managers could demonstrate to the Department of Defense that fuel cells operating on liquid carbonaceous fuels were feasible. Consequently, the methanol fuel cell was shaped both by ARPA's arbitrary timetable for results and by laboratory test conditions far less demanding than those required to make fuel cells a success in the vastly more challenging realms of the battlefield and the commercial marketplace.

The development of terrestrial methanol fuel cell technology also illustrates the divide between ARPA and IDA assumptions of the Army's fuel cell requirements and the armed service's actual needs. Contrary to expectations, the Army was concerned with economic issues even in the special fuel cell applications where the special qualities of silent, cool operation were supposed to offset cost. After all the effort, and quite apart from considerations of performance, the Electronic Components Laboratory considered Esso's methanol cell unattractive because of its reliance on platinum catalyst. Despite the fact that Electronics Command rejected the technology for further development, Esso continued work on the methanol cell into 1966 as part of its contractual obligations under Project Lorraine. Without a development sponsor, the device emerged into pre-prototype form a true technological orphan. Weighing 94 pounds without fuel, the device was far too heavy to be "manpacked."[37]

Despite spending at least $8 million on basic and applied research on fuel cells by the end of Fiscal Year 1964, ARPA did not understand the crucial relationship between the appliance and the power source, how electrical demand of a given appliance determined the basic physical principles of fuel cell electrochemistry.[38] This was largely a result of the agency's linear style of management and treatment of "basic" and "applied" research. As General Electric's Schenectady team eventually came to understand, fuel cell development demanded a techno-scientific approach. Technology needed to be extensively tested, scrutinized under realistic operating conditions and modified accordingly. Making durable fuel cell hardware was an activity in which the search for "physical principles" and "fundamental engineering principles" blended together in an arduous, reciprocal process, one in which clear-cut solutions were rare.

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[37] G. Ciprios, "Methanol Fuel Cell Battery," in *Proceedings: Twentieth Annual Power Sources Conference, 24-26 May 1966* (Red Bank, NJ: PSC Publications Committee, 1966), 48.

[38] Memorandum by John H. Huth, "Comments on IDA Report R-103 by R. Hamilton and G. Szego," 2 March 1964, Box 4, Project Lorraine-Energy Conversion, 2, National Archives and Records Administration II, College Park, MD. Expenditures on fuel cells constituted the lion's share of spending on energy conversion technology in Project Lorraine, which totaled $14.5 million through Fiscal Year 1964. By way of comparison, spending on materials sciences in this period averaged around $20-$25 million per year. ARPA's total annual budget in the first half of the 1960s fluctuated between a low of $186 million in Fiscal Year 1962 to a high of $278 million in Fiscal Year 1965, remaining in the $270 million range between Fiscal Years 1964-1966; Richard J. Barber Associates Inc., *The Advanced Research Project Agency, 1958-1974*, V-1, VI-1.

For ARPA managers, IDA systems analysts, Army administrators and industrial contractors steeped in the teleology of research and development, the terrestrial hydrocarbon fuel cell program was a disillusioning experience. Few anticipated that maintaining an invariant chemical environment within fuel cells would become increasingly difficult as they were piled into full-sized stacks. As this occurred in the late 1960s, the more perceptive researchers learned that virtually all the assumptions that underpinned the Department of Defense's terrestrial fuel cell program in 1960 were flawed.

Finding a Mission for the Army Fuel Cell

In 1965, the Army research and development bureaus considered the fuel cell technologies they had inherited from Project Lorraine. The direct hydrocarbon fuel cell program had ended inconclusively, leaving the methanol and indirect reformer-fuel cell concepts as the only immediate avenues for terrestrial fuel cells consuming carbonaceous substances. Though Esso's methanol fuel cell was regarded by many researchers including Ernst Cohn as the most advanced system employing an oxygenated hydrocarbon as of mid-1963, the Army's Electronics Components Laboratory regarded it as too heavy and costly.[39]

This left the reformer-fuel cell combination, considered by the Army as the quickest way to use hydrocarbons in fuel cells. Allis-Chalmers and Engelhard had built such a system using ARPA funds as part of Project Lorraine. When it performed poorly in early testing, Army planners turned to the hydrazine fuel cell, a technology that the Army's Mobility Command had been investigating independently of Project Lorraine since 1962.[40] The Army believed the design could fulfill the functions once ascribed to the methanol system, serving as an interim technology that could both provide useful service in the field and supply valuable lessons relevant for direct hydrocarbon fuel cell technology.

Little is known of the Army's fuel cell program. Appleby does not mention military reformer/fuel cell and hydrazine fuel cell technology at all in either the *Fuel Cell Handbook* or a 1991 review of the Army's fuel cell program.[41] This is a glaring omission, for a considerable amount of engineering work was devoted to these technologies, particularly the hydrazine fuel cell, which received more attention than any design apart from hydrogen-oxygen types in the 1960s.[42] The neglect is not surprising, given that both technologies were "dead-ends." Yet their development can reveal much of the psychology of interim fuel cell technology in fostering expectations of future technological progress.

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[39] Ernst Cohn, "Interdepartmental Energy Study: Chemical and Biochemical Fuel Cells," 19 August 1963, Record Number 13761: Propulsion: Auxiliary Power: Fuel Cells, 20, NASA Headquarters Archive.

[40] James R. Huff and John C. Orth, "The USAMECOM-MERDC Fuel Cell Electric Power Generation Program," in *Fuel Cell Systems II: 5th Biennial Fuel Cell Symposium sponsored by the Division of Fuel Chemistry at the 154th Meeting of the American Chemical Society, Chicago, Illinois, September 12-14, 1967* (Washington, D.C.: American Chemical Society, 1969), 321.

[41] A.J. Appleby, "Fuel Cells for Tactical Battlefield Power," *IEEE AES Systems Magazine* (December 1991): 49-55; A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), viii.

[42] E.J. Cairns and H. Shimotake, "Recent Advances in Fuel Cells and Their Application to New Hybrid Systems," *in Fuel Cell Systems II: 5th Biennial Fuel Cell Symposium sponsored by the Division of Fuel Chemistry at the 154th Meeting of the American Chemical Society, Chicago, Illinois, September 12-14, 1967*, 401.

Like ARPA's managers, Army administrators assumed that research and development was a linear, objective process that, when properly planned, yielded the tools the armed service required. Electronics Command's deputy commander, Brigadier-General Paul A. Feyereisen, held that "objectivity" could be achieved if technology was "banged" against missions and doctrine as a blacksmith might employ a hammer and anvil in forging a horseshoe, shaping the malleable artifacts to conform to the wishes of the systems planner. He also believed that national defense missions, doctrine and technology normally would not change drastically in what he termed the "current time period," from the present to four years into the future. This was still substantially fixed, he claimed, in the "mid-range period" from four to eight years. It was only in the eight to 12-year time frame that mission, doctrine and technology became "flexible."[43]

This was more a prescription than a description, particularly where fuel cell research and development was concerned. As we have seen, Project Lorraine stemmed not from an "objective" need but rather a complex mix of political, cultural and economic factors. Fuel cells were a technology in search of a role, yet experiments with direct hydrocarbon oxidation proceeded on the basis of expectations derived from similarity judgments made during the earliest stages of prospective testing in the late 1950s. The methanol and indirect systems were interim solutions pursued because they were the most easily developed, not because they met pressing needs or were objectively superior. As the British experience illustrates, fuel cell research programs once begun were difficult to abandon outright once institutional sponsors made investments in them.[44]

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[43] Paul A. Feyereisen, "Systems Approach to Army Communications-Electronics," January 1966, CECOM Historical Research Collection TS, 87-ECOM-66, 3, 5.

Feyereisen's assumptions of the rationality and objectivity of research and development, as well as the belief in the stability of mission and doctrine, would be challenged during the Army's fuel cell program after 1965. The war in Vietnam produced a major revision in U.S. military tactics and strategy, creating strong pressures to deliver usable combat hardware and disrupting the Army's short-term and long-term fuel cell research and development objectives. The result was that Army managers made judgments based not wholly on objective technical criteria but on the same kinds of technopolitical calculations that had set researchers on the path of least engineering resistance during Project Lorraine. As the Army adjusted to guerilla warfare in Southeast Asia, the missions against which fuel cell technology was to be "banged" were in flux. This conflict had relatively more scope for infantry and less for the large vehicle-based formations around which the Army had been built in preparation for conventional warfare on the European battlefield. While some in the Army remained enamored with the concept of a universal hydrocarbon energy converter of the sort envisioned by the IDA, the physical obduracy of these systems, the perceived simplicity of the hydrazine fuel cell and rapidly changing military doctrine served to make the requirement for power sources for "manpacked" radios relatively more important after 1965.

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[44] The case of the NRDC and the Bacon cell is a good example of this. In 1954, the Earl of Halsbury had observed that years of research on the Bacon cell had proved there were no simple solutions in developing fuel cells. Less than two years later, he signed on to the Bacon project, although no "breakthroughs" had been made, remarking to Bacon that he had always wanted to support him "if need arose." This occurred at a time when there were few genuinely good technological innovations available for the NRDC to develop that were not already being exploited by industry; Halsbury to Bacon, 28 February 1956, Bacon TS, Research and Development, National Research Development Corporation/Marshall's of Cambridge, Correspondence, B. 273; The Earl of Halsbury, "Strategy of Research," *Research* 7 (December 1954): 480.

The decision to develop hydrazine fuel cell was triggered by the Army's inability to develop indirect reformer-fuel cell systems. By the mid-1960s, each Army laboratory had an indirect system under prototype development. With support from ARPA, Mobility Command's Engineer Research and Development Laboratory (ERDL) began work with Allis-Chalmers and Engelhard on a five-kilowatt unit in 1963, while the Electronics Command Laboratory contracted with Pratt & Whitney for a 500-watt reformer-fuel cell in 1964.[45] Conceiving the Allis-Chalmers/Engelhard system as a way to allow engineers to exploit existing pieces of reformer and alkaline fuel cell hardware while they struggled to master direct hydrocarbon electro-oxidation, ARPA planners also wanted to use the technology as a platform to test components they hoped to employ in the direct hydrocarbon fuel cell when it was perfected. Typically, they claimed that the reformer-fuel cell would be able to stand on its own merits.[46]

The process of selecting a contractor to build the reformer-fuel cell, however, was not driven primarily by technical merit. Time, money and military-industrial political relations were at least as important. Of four competing companies, ARPA and the Army deemed Allis-Chalmers best suited to supply fuel cell modules and control equipment and integrate the various component, believing these subsystems drew less power, known as parasitic demand, from the overall output. At $400,000, Allis-Chalmers had submitted the lowest bid of the four contenders by a considerable margin, comprising less than a third of those of Pratt & Whitney and General Electric.[47] These companies had more elaborate proposals that ARPA judged unlikely to be completed in time to meet its strict deadline. Moreover, Pratt & Whitney preferred to develop its own reformer rather than collaborate with Engelhard. But as a naval officer attached to ARPA's Materials Sciences Offices noted, the ERDL was aware that General Electric had already received generous ARPA funding for fuel cell research, while Pratt & Whitney had strong industrial allies including Ford, TRW and Columbia Gas in its own reformer-fuel cell project. A further attraction of Allis-Chalmers' fuel cell technology was that it had been used in vehicular applications.[48] Taken together, this suggests that cost and an informal policy of military-industrial affirmative action were important factors in the contract selection process.

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[45] Stephen J. Bartosh, "500-Watt Indirect Hydrocarbon System," T.G. Kirkland, "5 KW Hydrocarbon-Air Fuel Cell Power Plant," in *Proceedings: Twentieth Power Sources Conference 24-24-26 May 1966* (Red Bank, NJ: PSC Publications Committee, 1966), 31, 35.
[46] Memorandum by Charles F. Yost, "Subject: Electrochemistry (5 KW Reformer Fuel-cell Unit)," 1 February 1963, Box 4, AO 430-Allis-Chalmers, 1-2, National Archives and Records Administration II, College Park, MD.

Although Army and ARPA planners believed the reformer-fuel cell system was the simplest way of using hydrocarbons, the fuel purification process merely externalized the electrochemical complexity of the direct hydrocarbon system. As a Mobility Command systems analysis argued in 1967, reforming was ranked the most difficult of all the various fuel cell processes.[49] Researchers made two key assumptions: first, that reformers could convert oily logistics fuels to hydrogen that could then be used in fuel cells with carbon-sensitive alkaline electrolytes; and second, that integrating a reformer with a fuel cell posed a tolerable engineering challenge. Neither of these assumptions held under the tight fiscal and time constraints imposed by the ERDL. Although the reformer-fuel cell project had been started in the summer of 1963, the system had not yet been operated as a complete unit by the spring of 1965 and only individual components had been tested.[50]

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[47] Oscar P. Cleaver to John Huth, 6 March 1963, AO 430-Allis-Chalmers, 2. The bid price was the last item mentioned in the Army Engineer Research and Development Laboratory assessment of the Allis-Chalmers system.

[48] Memorandum by M.X. Polk, "Subject: Hydrogen Reformer, Air Fuel Cell Contract," 12 March 1963, AO 430-Allis-Chalmers, 1-2. The company's vehicular applications were one-off demonstrators including a tractor tested in 1959 and a refitted electric golf cart.

[49] Huff and Orth, "The USAMECOM-MERDC Fuel Cell Electric Power Generation Program," in *Fuel Cell Systems II*, 318.

By 1966, the project had stalled. Allis-Chalmers failed to live up to the ERDL's expectations, proving incapable of integrating the components of the fuel cell itself, let alone the reformer system. Bacon's contacts in the ERDL reported that the reformer-fuel cell combination never worked properly owing mainly to failings in the fuel cell, which were in turn due largely to poor electrode quality control. Consisting of four modules of cells linked in series, the device suffered from uneven performance and occasional cell reversal, where weak cells were "driven" by others in the array into electrolysis cells. On the other hand, the reformer itself worked well.[51] No difficulty was encountered running individual fuel cells, but they would not operate uniformly when arranged in stacks. As a system, the reformer-fuel cell was bulky, noisy, overweight, complex and inefficient. Its pumps, control equipment and the scrubber required to clean the alkaline electrolyte of impurities turned out to exert a considerable parasitic power demand after all. The unit required 40 minutes to start and was unable to operate at full output for more than a few minutes owing to the unreliability of the individual components.[52] Nevertheless, Army engineers claimed the exercise had "proved the feasibility" of the reformer-fuel cell concept, providing valuable knowledge for future programs.[53]

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[50] T.G. Kirkland and W.G. Smoke, Jr., "5 KVA Hydrocarbon-Air Fuel Cell System Test," in *Nineteenth Annual Power Sources Conference, 18-20 May 1965* (Red Bank, NJ: PSC Publications Committee, 1965), 26.

[51] F.T. Bacon, "Energy Conversion Limited Visit Report VR 136: Visit to America," 13-24 March 1967, Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.760, 7-8.

In fact, the Army's hydrocarbon fuel cell program was doomed by a problem that transcended the various combinations of electrolytes and direct and indirect systems attempted throughout the 1960s. The military's chief logistics fuels, particularly Jet Propellant-4 (JP-4), were simply too chemically complex for reformer technology to process. Originally developed by the U.S. Air Force, JP-4 had been designed for wide availability and maximum performance in aircraft. As a result, it contained more than 30 different substances, including anti-icing agents, anti-oxidants and corrosion inhibiters, as well as non-hydrocarbon substances such as sulfur.[54] Not only did sulfurous JP-4 corrode reformer catalysts during the fuel conversion process, but the resulting hydrogen-rich gas also retained sufficient sulfur to damage fuel cell electrodes.[55]

Like industry researchers during Project Lorraine, Army engineers reverted to simpler fuels. During initial tests of the reformer-fuel cell, they substituted JP-4 with naphtha, a sulfur-free light fraction of refined petroleum.[56] However, this was an expensive fuel hardly representative of the substances in the Army's supply chain.

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[52] The Pratt & Whitney reformer-fuel cell system was somewhat more successful, operating as a unit for about 100 hours at its rated capacity; Stephen J. Bartosh, "500-watt Indirect Hydrocarbon System," in *Proceedings, Twentieth Annual Power Sources Conference, 24-25-26 May 1966* (Red Bank, NJ: PSC Publications Committee, 1966), 33.

[53] T.G. Kirkland, "5 KW Hydrocarbon-Air Fuel Cell Power Plant," *in Proceedings: Twentieth Annual Power Sources Conference*, 36, 39.

[54] Agency for Toxic Substances and Disease Registry, "Toxicological Profile for Jet Fuels JP-4 and JP-8," Chemical and Physical Information, 64, 69, http://www.atsdr.cdc.gov/toxprofiles/tp76.html, accessed 20 December 2005.

[55] News Release, U.S. Army Electronics Command, 2 March 1967, CECOM Historical Research Collection TS, 2.

[56] Kirkland and Smoke, Jr., "5 KVA Hydrocarbon-Air Fuel Cell System Tests," in *Proceedings: Nineteenth Annual Power Sources Conference, 18-20 May 1965*, 28.

Nor were researchers nearer to solving the puzzle of direct hydrocarbon oxidation. The heavier and more complex the fuel, the greater the quantity of platinum required to catalyze the reaction.[57] The path of least engineering resistance led once more into a confusing thicket of electrochemical complexity and unsatisfactory compromises. Unable to develop suitable direct or indirect hydrocarbon fuel cells capable of meeting the Army's immediate requirements, engineers looked to the hydrazine fuel cell after 1965 as yet another technological hedge.

Technological Symbolism: The Hydrazine Hedge

The Army's doctrinal justification for the hydrazine system was similar to the one it advanced for the methanol fuel cell. Army planners saw it as an interim technology that could reconcile their long and short-term power source goals. A costly and volatile inorganic (non-carbonaceous) substance then used mainly by NASA as a rocket fuel, hydrazine, like methanol, had no logistics value. Army planners knew that hydrazine was too expensive for use in large multi-kilowatt fuel cells. They were nevertheless attracted by its operating properties, for hydrazine could be electro-oxidized relatively easily compared with the logistics fuels and it produced a high current density. Believing hydrazine would present fewer obstacles for fuel cell operating systems than hydrocarbons and alcohols, researchers conceived it, like the methanol design, as a "direct" system in which a liquid fuel was injected into the electrolyte. With Mobility Command unable to realize its primary objective of developing a general-purpose hydrocarbon fuel cell for stationary generator and vehicles in the short term, planners sought secondary roles for the hydrazine fuel cell.

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[57] H.A. Liebhafsky, "The Electrocatalyst Problem in the Direct Hydrocarbon System," in *Proceedings: Twentieth Annual Power Sources Conference, 24-25-26 May 1966* (Red Bank, NJ: PSC Publications Committee, 1966), 1.

Its value, held Mobility Command, lay in its silent operation and readiness for prototype development and early field trials.[58] Though the Army was still committed to research on hydrocarbon fuel cells, its engineers believed in 1966 that the simplicity of the hydrazine system would allow it to be the "first fully developed" fuel cell available for deployment in Vietnam.[59]

Army researchers regarded the hydrazine fuel cell as both a practical power source and as a research tool. They thought it superior to conventional batteries both for soldier-portable or "manpacked" communications and surveillance appliances and for electric vehicles. Army engineers also hoped the hydrazine system could provide experience useful in developing the direct hydrocarbon fuel cell. Hydrazine fuel cells first appeared attractive to the ERDL as a test power source to help perfect automotive electric drive. Army engineers believed that hydrazine fuel cells could simulate the performance characteristics of direct hydrocarbon fuel cells under electric motor loads. At such time as direct hydrocarbon cells were perfected, they reasoned, these could be coupled to such motors with minimal difficulty.[60]

In short, Army researchers made a similarity judgment between hydrazine and hydrocarbon fuel cells. They expected hydrazine to behave like a directly-injected hydrocarbon in a fuel cell under load conditions with fewer chemical complications. Like many previous assumptions of terrestrial fuel cell performance, this hypothesis stemmed from early tests of simple laboratory devices. But as engineers would soon discover, hydrazine not only was no easier to manage in a fuel cell than hydrocarbons, it presented wholly new challenges. A highly toxic nitrogenous substance, it is more dangerous than ammonia and more than 1000 times more poisonous than gasoline. Hydrazine is very sensitive to temperature change and easily decomposes into ammonia. Because a wide variety of materials will catalyze hydrazine, such fuel cells had to be kept scrupulously clean to prevent premature fuel decomposition. As one contemporary British study indicated, construction materials for a hydrazine fuel cell meant for service in arctic or temperate climates might not be suitable for a device intended for operation in the tropics.[61]

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[58] Edward A. Gillis, "Hydrazine-Air Fuel Cell Power Sources," in *Proceedings: Twentieth Annual Power Sources Conference, 24-25-26 May 1966* (Red Bank, NJ: PSC Publications Committee, 1966), 44.

[59] Huff and Orth, "The USAMECOM-MERDC Fuel Cell Electric Power Generation Program," 321; Historical Branch Headquarters, *Annual Historical Summary of United States Army Electronics Command, 1 July 1964-30 June, 1965*, 1 March 1967, CECOM Historical Research Collection TS, Annual Historical Data, 1012.

[60] Edward A. Gillis, "Hydrazine-Air Fuel Cell Power Sources," in *Proceedings: Twentieth Annual Power Sources Conference, 24-25-26 May 1966*, 41. One 20-kilowatt hydrazine fuel cell was developed for use with an electric truck at Fort Belvoir. This was a hybrid system in which the fuel cell was combined with a 20-kilowatt battery. When maximum power was called for, the vehicle could draw on both power sources. During periods of low demand, the fuel cell would recharge the battery; F.T. Bacon, "Energy Conversion Limited, Visit Report VR 136: Visit to America," 13-24 March 1967, Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.760, 7.

Hydrazine's volatility posed unique challenges for the design of fuel cell control equipment. Like all fuel cell systems that introduced chemical fuels directly into the electrolyte, the hydrazine design required sophisticated auxiliary devices to inject fuel, remove water and cleanse the electrolyte. As Army researchers gained more experience testing scaled-up hydrazine fuel cells in the latter half of the 1960s, they realized that the duty cycle, or the load demand of a particular appliance, had great consequences for the chemical balance of a given fuel cell and, thus, for control equipment. Not all duty cycles were the same. They varied according to the type of appliance and the way in which it was used. Devices like radars imposed a more or less steady demand on the power source, while others, like small infantry radios, drew power intermittently. The load profile of a specific appliance had unique consequences for the chemical balance of a fuel cell, and, thus, its service life. These dynamics further varied according to the type of fuel, electrolyte, and electrode materials used in the fuel cell reactor.

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[61] "DMR-C4 (e) 7451: General Comparison Between Hydrazine Hydrate and Liquid Hydrocarbon Fuels," 6 March 1968, Bacon TS, Section, B, Research and Development, Research and Development Topics, 'Hydrazine and Ammonia', B.1050, 7. Materials that react catalytically with hydrazine include monel, zinc, copper alloys, iron, magnesium, stainless steels with more than .5 per cent molybdenum and some aluminum alloys.

Control equipment had to be designed to take these changing electrochemical conditions into account. Only after all the various components had been assembled into the power source and it was mated to an appliance could a fuel cell be considered a complete system. Accurate judgments regarding reliability and durability could be made only when all the pertinent electrochemical factors present. Because researchers historically approached fuel cell development in a piecemeal fashion, however, control equipment was typically the last subsystem to be considered. It was as vital a component as any other, but with research funds restricted as the Vietnam War dragged on and with political pressure mounting to deploy fuel cell systems for combat trials as soon as possible, it represented a price in time and resources that the Army laboratories were increasingly unable to pay.

The most important Army fuel cell program was Mobility Command's Union Carbide-built 300-watt generator, the only fuel cell to see service in Vietnam. The life cycle of this technology shows how prospective testing reinforced a reductive approach among designers, fostering a simplistic view of a fuel cell as an energy conversion unit rather than a component of a power source-appliance system. The resulting high expectations for the technology and assumptions of the military value of hydrazine fuel cells would quickly be dispelled when this system was deployed in combat. This fuel cell originated in response to an Army requirement developed in 1966 for a silent, light power source for radio equipment, particularly the AN/PRC-47.[62] Built by the Collins Company, this was a large, powerful radio used mainly by the Navy and Marine Corps in vehicles, fixed installations and as a soldier-borne unit. Though considered a "manpack" radio, the 45-pound (20 kilogram) unit and its 17-pound (7.7 kilogram) silver-zinc BB-451/U battery was too heavy for an individual to carry on long patrols in tropical terrain. The system typically required two soldiers, one carrying the receiver/transmitter and the other packing the batteries.[63] In Vietnam, the AN/PRC-47 was used by Marine "forward air controllers," small groups of soldiers who stealthily reconnoitered enemy positions and guided attacks by aircraft. The AN/PRC-47 was favored for this role owing to its high power and long range. But it also quickly drained its power source.[64] So important did the Army regard long-lived and reliable power sources that it designated the Union Carbide 300-watt fuel cell prototype a crash project and gave it a high-priority status known as ENSURE (Expedite Non-Standard Urgently Required Equipment).[65]

The earliest version, produced in only five months, impressed Army engineers. They cited successful trials of the 33-pound (15 kilogram) unit in audible noise, high temperature, humidity, altitude and inclined operation tests. Proclaiming it the most advanced fuel cell of any type then in operation, the Army deemed it robust enough to be placed in a limited production run of 100 units and pressed it into service in Vietnam in late 1966.[66]

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[62] Gillis, "Hydrazine-Air Fuel Cell Power Sources," in *Proceedings: Twentieth Annual Power Sources Conference, 24-25-26 May 1966*, 44.

[63] Historical Branch Headquarters, "Power Sources," *Annual Historical Summary of United States Army Electronics Command, 1 July, 1965-30 June, 1966*, 20 April 1969, CECOM Historical Research Collection TS, Annual Historical Data, 1007; S.M. Chodosh, M.G. Rosansky and B.E. Jagid, "Metal-Air Primary Batteries: Replaceable Zinc Anode Radio Battery," in *Twenty-First Annual Power Sources Conference, 16-17-18 May 1967* (Red Bank, NJ: PSC Publications Committee, 1967), 103. I have drawn additional information on the AN/PRC-47 from amateur radio enthusiasts and hobbyists; home.comcast.net/~ka4Koe/greenies,hereford.ampr.org/millist/m22.html#a4313,www.nj7p.org/history/portable.html#a008, accessed 14 March, 2007.

[64] www.pacificsites.com/~brooke/NYH_PRC47.htm, accessed 14 March, 2007.

[65] F.G. Perkins, "Experience with Hydrazine Fuel Cells in SEA," in *Proceedings: Twenty-Fourth Annual Power Sources Conference, 19-20-21 May 1970* (Red Bank, NJ: PSC Publications Committee, 1970), 202.

Like all fuel cells, the full-size hydrazine fuel cells displayed adverse physico-chemical phenomena under long-term tests that researchers had not noticed in earlier prospective testing. These were serious enough to cause major delays. When such fuel cells were coupled with an appliance and subjected to simulated operating conditions, the hydrazine constantly underwent side reactions, which could occur even when the fuel cell was not under load.[67] In conditions of high temperature and high fuel concentration, the electrical energy released by the chemical reaction could decompose unspent hydrazine into ammonia and hydrogen, resulting in efficiency losses. In such circumstances, the hydrazine itself might also evaporate, posing an inhalation hazard for the operator.[68]

These factors impinged upon the design of control equipment. Union Carbide was determined to develop a general-purpose fuel cell that could cope with a variety of load profiles, meeting every possible operating requirement in all climates.[69] Its engineers first tried using a mechanical feed device of sufficient sensitivity and robustness to cope with the hydrazine system's very low fuel consumption and the rough handling and conditions it was likely to experience in the field. But since the viscosity of hydrazine varies according to temperature, it was difficult to develop a standard fuel feed system that could be used in any climate.[70] The duty cycle of two-way radios further complicated the design of fuel control equipment because these appliances drew more power to transmit than to receive, a pattern that further varied depending on how often the radio was used. A mechanical fuel control system was adequate for a fixed power level, but it supplied too much fuel under conditions of partial load as would be encountered with a radio.[71]

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[66] Edward A. Gillis, "Hydrazine-Air Fuel Cell Power Sources," in *Proceedings: Twentieth Annual Power Sources Conference, 24-25-26 May 1966*, 44-45.

[67] D.P. Gregory, "A Review of Factors Influencing Policy Towards Hydrazine Fuel Cells: Presentation to the ECL Technical Committee," 8 June 1966, Bacon TS, Section B, Research and Development, Research and Development Topics, 'Hydrazine and Ammonia,' B.1049-1050, 2-3.

[68] George E. Evans, "Hydrazine-Air Fuel Cells," *in Proceedings: Twenty-First Annual Power Sources Conference, 16-17-18 May 1967* (Red Bank, NJ: PSC Publications Committee, 1967), 34.

[69] Ibid., 36. In 1961, Union Carbide fuel cell researchers declared that given the current state of the art, general-purpose fuel cells were impossible. Fuel cells then had to be specially built to suit each new application; H.W. Holland, "Carbon Electrode Fuel Cell Battery," in *Proceedings, Fifteenth Annual Power Sources Conference, 9-11 May 1961* (Red Bank, NJ: PSC Publications Committee, 1961), 28.

Although Union Carbide researchers recognized that hydrazine fuel cell control equipment had to be tailored to accommodate the specific duty cycle of a given appliance, the company was unable to reconcile the technological implications of this conclusion with its larger aspirations for the technology. By 1968, Union Carbide remained hopeful that it could develop fuel control equipment with a multi-purpose capability for a "broad range" of end-use applications even as its researchers acknowledged that this would make the power source larger, more complex and more costly.[72] By 1969, the company was forced to moderate its claims. Its engineers admitted the hydrazine fuel cell was not suitable for cold climates and that it offered advantages only in special applications. The control unit of the 300-watt unit ultimately employed an automatic system to detect voltage increases based on the concentration of hydrazine in the electrolyte, controlling the flow of fuel accordingly.[73]

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[70] Evans, "Hydrazine-Air Fuel Cells," *in Proceedings: Twenty-First Annual Power Sources Conference, 16-17-18 May, 1967*, 35.

[71] Preliminary work had not prepared researchers for the problems of scaling-up fuel control equipment. As one Union Carbide engineer observed, it was one thing to develop a fuel feeder that would operate well "on a relay rack in an air conditioned laboratory," something else again to build one that could withstand "salt-spray test, humidity-cycling test and…environmental extremes;" Evans, "Hydrazine-Air Fuel Cell Controls," in *Proceedings: Twenty-Second Annual Power Sources Conference, 14-15-16 May 1968* (Red Bank NJ: PSC Publications Committee, 1968), 1.

[72] Evans, "Hydrazine-Air Fuel Cell Controls," in *Proceedings: Twenty-Second Annual Power Sources Conference, 14-15-16 May 1968* (Red Bank NJ: PSC Publications Committee, 1968), 1.

In April 1969, some three years behind schedule, 20 300-watt units were shipped to Vietnam for trials.[74] Engineering compromises yielded a technology that did not possess the qualities of light weight and quiet operation that designers had assumed were intrinsic to it and which they believed made it useful for "man-portable" tactical roles. Noisy, smelly and weighing 40 pounds, seven pounds more than the 1966 version, the fuel cell was much heavier than the battery it was designed to replace and was unsuited for soldiers operating in forward positions close to enemy troops. After years of experience, the Army learned that in tropical conditions, individual pieces of equipment weighing more than 20 pounds could not be considered "man-portable." The Union Carbide hydrazine fuel cell was instead classified as "man-manageable," in that it could be hauled by an individual soldier intermittently to distances of between 50 to 100 metres.[75] Consequently, it was used mainly in rear base areas powering large appliances like command post radios and ground surveillance radars. In such roles, light weight and quiet operation were of little consequence, for the fuel cell functioned as a part of base infrastructure. Like other major pieces of equipment, it was transported in aircraft, boats or land vehicles, not on the backs of soldiers.[76] Furthermore, these facilities were difficult to conceal from the enemy due to their large size and regular vehicular traffic. In such applications, the hydrazine fuel cell offered no advantage over internal combustion engine generators to offset their reliance on exotic fuel. The Army admitted that in such roles, the value of silent operation, for long an important if not the prime justification for special-purpose fuel cells using special fuels, was difficult to quantify and was more likely psychological than anything else.[77]

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[73] George E. Evans and Karl V. Kordesch, "Hydrazine-Air Fuel Cells," *Science* 158, no. 3805 (1 December 1967): 1151-1152.

[74] F.G. Perkins, "Experience with Hydrazine Fuel Cells in SEA," in *Proceedings: Twenty-Fourth Annual Power Sources Conference, 19-20-21 May 1970* (Red Bank, NJ: PSC Publications Committee, 1970), 202.

[75] Ibid., 203.

[76] The Union Carbide fuel cell generator was also used in mobile command posts in helicopters and patrol boats, applications where silent operation was similarly irrelevant.

The Electronics Components Laboratory and Monsanto experienced similar problems in their hydrazine fuel cell effort. Because their fuel cell was considerably smaller, they faced greater electrochemical engineering challenges than Union Carbide and the ERDL. As Union Carbide researcher Karl Kordesch noted, the technical issues of fuel control were even more difficult in smaller systems because their consumption was so low. A 100-watt unit required only one milliliter per minute. Metering such miniscule fuel flows was further complicated by the rough handling and non-horizontal orientation the power unit could be expected to undergo while strapped to a soldier's back.[78] These issues led the ECL and Monsanto to consider a technological approach different from that of the ERDL and Union Carbide. While both Army laboratories and their contractors gradually became aware that the duty cycle of a specific appliance had important consequences for the design of its fuel cell power source, the ECL seems to have developed a stronger grasp of this relationship where radios were concerned, possibly as a result of the fuel control challenges it faced. Monsanto ECL engineers decided to develop a hybrid battery-fuel cell that smoothed or "shaved" the demand peaks of radios. The fuel cell charged the battery during periods of low demand and then combined with it to provide the heavy transmit load. This protected the fuel cell from the stress of sudden and irregular power demand that wreaked havoc with overall chemical equilibrium.[79] Conversely, such hybrids offered few advantages when an application drew steady continuous power from a power source.[80] In the load-leveling battery-fuel cell hybrid, Army and industry researchers in essence declared the concept of a general-purpose fuel cell impracticable.

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[77] F.G. Perkins, "Experience with Hydrazine Fuel Cells in SEA," 203.
[78] Evans and Kordesch, "Hydrazine-Air Fuel Cells," 1151-1152.

Even with this innovation, ECL and industry engineers, like their ERDL counterparts, could not quickly overcome the inherent shortcomings of the hydrazine fuel system. Unable to control destructive chemical side reactions, researchers opted for a radical solution in one of the final designs. The fuel cell itself was transformed into a disposable power block with a useful life of only 750 to 1000 hours, to be replaced as needed. The durable components of the technology were instead the power processing module and the auxiliary control systems, which had a lifetime of more than 5000 hours.[81] In a sense, then, this particular fuel cell concept ended up as virtually a kind of disposable primary battery.[82] While an Army evaluation team appreciated the "intended flexibility" of the hybrid device, it left much to be desired in terms of cost-effectiveness.[83] There were no major field trials in Southeast Asia of any of Electronics Command's "manpack" fuel cell systems.

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[79] Ibid., 1010.

[80] Galen R. Frysinger, "Integrated Cell Stacks," in *Proceedings, Twenty-Second Annual Power Sources Conference, 14-15-16 May 1968* (Red Bank, NJ: PSC Publications Committee, 1968), 26.

[81] R.E. Salathe, "Evolution of the Replaceable Hydrazine Module as a Basic Building Block," in *Proceedings: Twenty-Fourth Power Sources Symposium, 19-20-21 1970* (Red Bank, NJ: PSC Publications Committee, 1970), 204.

[82] Bacon reported that the Army simply threw away the alkaline electrolyte of hydrazine fuel cells when it became contaminated with carbon dioxide in ambient air; Galen R. Frysinger, interview by Francis Thomas Bacon, 17 March 1967, Bacon TS, Section F, Visits and Conferences, 'Visit to USA,' F.24.

The Army's decision to develop the hydrazine fuel cell was conditioned by its perception that the technology represented the path of least engineering resistance in a program burdened by past failures and with limited resources as the war in Southeast Asia intensified. As early as 1964, the Electronics Components Laboratory's request to Army Materiel Command for 28 additional personnel and $2.6 million to support the "intensified research effort" was denied. Repeated requests for more funds and personnel were ignored. Well before the Johnson administration began the escalation of the war in 1964, the ECL laboratory had been losing personnel, 117 in all since 1960, representing 21 per cent of its overall staff. Although the Power Sources division avoided the worst of the cuts, it could not avoid making reductions as well.[84] Furthermore, the laboratory did not have its own chemists and electrochemists and had to recruit entirely from outside Electronics Command, reflecting the larger trend in the United States. Coinciding with the withdrawal of U.S. forces from Vietnam that began in 1969, Electronics Command experienced further reductions in personnel and funds.[85]

In these circumstances, Army researchers considered hydrazine technically "sweet," valuing its high reactivity over its high volatility, toxicity and cost. On a visit to the United States in March 1967, Francis Bacon reported that some Army researchers had never been enthusiastic about using hydrocarbons in fuel cells and much preferred to work with the nitrogenous substance.[86] Some veteran fuel cell workers reflected with a certain nostalgia for the high power these systems produced.[87] With the hydrocarbon programs stalled, the hydrazine fuel cell provided the Army service laboratories with badly-needed successes.

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[83] Historical Branch Headquarters, "Electronics Components Laboratory," in *Annual Historical Summary of United States Army Electronics Command, 1 July, 1969-30 June, 1970*, CECOM Historical Research Collection TS, Annual Historical Data, 24.

[84] U.S. Army Electronics Command, "Commander's Operations Report," February 1966, CECOM Historical Research Collection TS, Annual Historical Data, 1-15-1-16.

[85] Overall, the Command's authorized civilian strength was lowered by 1,142 in Fiscal Year 1970 from the previous year. Within the Electronics Components Laboratory, eight personnel were lost. Historical Branch Headquarters, *Annual Historical Summary of United States Army Electronics Command, 1 July, 1969-30 June, 1970*, CECOM Historical Research Collection TS, Annual Historical Data, 3, 220.

In some quarters, however, the hydrazine fuel cell concept was regarded as little more than an effort in public relations. Writing in 1966, D.P. Gregory of the British fuel cell consortium Energy Conversion Limited questioned the rationale of using this technology as a means to gain experience with direct fuel cell systems. He believed that such demonstrations were purely political and meant to show that continuously fed electrochemical systems in general were "conceptually practical." In this view, the promoters of the hydrazine system were using it to simulate the operation of a direct hydrocarbon fuel cell when in fact the respective underlying electrochemical dynamics of these technologies were considerably different. Gregory believed that the fact that hydrazine systems were likely to be the first practical terrestrial fuel cells was of considerable political significance, allowing designers to claim that the goal of a direct hydrocarbon fuel cell was near.[88]

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[86] Galen R. Frysinger, interview by Francis Thomas Bacon, 17 March 1967, Bacon TS, Section F, Visits and Conferences, 'Visit to USA,' F.24.

[87] B.S. Baker aptly recalled the trade-offs presented by the hydrazine fuel cell. He noted that researchers "even today" would be impressed by the technology's power output, adding that "lifetime, both of the fuel cell and its operators, is another question;" Baker, "Grove Medal Acceptance Address," *Journal of Power Sources* 86 (2000): 9.

[88] D.P. Gregory, "A Review of Factors Influencing Policy Towards Hydrazine Fuel Cells: Presentation to the ECL Technical Committee," 8 June 1966, Bacon TS, Section B, Research and Development, Research and Development Topics, 'Hydrazine and Ammonia,' B.1049-1050, 3.

With the end of the Army's hydrazine experiment in the early 1970s, fuel cells vanished from the armed service's power sources agenda for the remainder of the decade. The Army's focus in electrochemical systems returned to primary and secondary batteries, though the service would investigate other types of fuel cell systems in the 1980s and 1990s. In some respects, hydrazine fuel cells represented a retrograde solution, for they employed an alkaline electrolyte. The first great post-war fuel cell boom had been launched in the late 1950s largely as a result of the publicity generated by alkaline fuel cells; the deficiencies of such systems, particularly their intolerance of carbon dioxide, had in turn helped stimulate efforts to develop acidic hydrocarbon fuel cells during Project Lorraine. Problems with that technology then led Army researchers back to alkaline electrolyte systems in the form of the hydrazine fuel cell. That, too, failed to demonstrate the expected long-term chemical stability and invariance that researchers had long believed distinguished fuel cells from galvanic batteries.

During the Power Sources Conference of 1972, Mobility Command's John B. O'Sullivan reflected on the history of the terrestrial fuel cell program. In seeking an explanation for the waxing and waning of expectations over the previous decade, he offered no single theme. But O'Sullivan did note the strong element of irrationality underlying the first flush of optimism that launched the "boom." Employing metaphors of pseudo-science, O'Sullivan described how the fuel cell had been sold as a "technological elixir" in the manner of the quack physician prescribing "patent medicines" to the credulous.[89] Part of the problem in the early days, he wrote, had been an "inverse relationship" between the variety of research approaches and the sum of "meaningful information." Fuel cell research and development had always been conducted with the expectation of revolutionary developments, the anticipation of an imminent breakthrough "just over the horizon." Yet every advance brought a new and complex array of compromises and tradeoffs.

While these were valid points, they revealed little of the motivations of the various government agencies willing to sponsor inconclusive research year after year. Part of the answer to the problem of why U.S. fuel cell research had boomed and busted in the 1960s and early 1970s was supplied in the details, rather than the thesis of O'Sullivan's paper. He provided a clue in his observation that American fuel cell research had been driven by the belief that fuel cells would have to use fossil fuels in order to "have a major impact upon our society." In contrast to Europe, where researchers had concentrated their efforts on the more modest goal of developing specialized fuel cells using exotic fuels, the original objective set by American promoters of terrestrial fuel cells was nothing short of replacing the incumbent internal combustion engine technology.[90]

What O'Sullivan did not address was how expectations for a miracle battery were generated, shaped and modulated during the various phases of research. As Michel Callon has noted in the French context, this was a process in which the work of researchers and engineers was conditioned by an interaction of the social with the physical. At each stage, technopolitical factors determined the research questions that were to be pursued and how they were to be addressed. Technical issues were simplified as fuel cell coalitions were built. Judgments of what constituted a successful fuel cell in terms of performance, affordability and durability were relative determinations based upon the socio-economic context within which they were formulated.[91]

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[89] John B. O'Sullivan, "Historical Review of Fuel Cell Technology," in *Proceedings: Twenty-Fifth Power Sources Symposium, 23-24-25 May 1972* (Red Bank, NJ: PSC Publications Committee, 1972), 149.
[90] Ibid., 150.

In the U.S., post-war work on fuel cell technology was characterized above all by its military-industrial nature. The seeds of the uniquely American dream of a universal hydrocarbon energy converter had been sown at the outset of Project Lorraine by the Army, the IDA and ARPA. This was based almost entirely on similarity judgments drawn from industry's experience with hydrogen fuel cell technology in the late 1950s, much of which had been developed with military funding. Subsequently, government planners enlisted the private sector in the hydrocarbon fuel cell program, encouraging the view that it would spawn a commercial dividend.

However, initial judgments of fuel cell technology made in the very earliest stages of prospective testing, from which all subsequent expectations flowed, had been based on standards that reflected military values more than any other. High performance, rather than cost or durability, had been what had initially attracted interest. The first sponsors of and customers for fuel cell technology had been military or, in the case of NASA, quasi-military.[92] In the early 1960s, the fact that platinum was expensive and scarce was less important to ARPA, the Army and industry than the fact it was the most active known catalyst. The electro-oxidation of chemically simple carbonaceous fuels in small acidic laboratory fuel cells using platinum catalyst fed hopes that a general-purpose energy converter could be built. This provided the political capital to allow a military-industrial "dream team" to coalesce around the concept of a direct hydrocarbon fuel cell, nourished by a steady though gradually diminishing stream of funding from the Department of Defense.

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[91] Michel Callon, "The State and Technical Innovation: A Case Study of the Electrical Vehicle in France," *Research Policy* 9 (1980): 364.

[92] Though technically a civilian agency, NASA had strong connections with the military-industrial complex. All of its astronauts and many of its technical personnel were active or former members of

As more sophisticated terrestrial fuel cell technology was developed in the early 1960s, the Army and ARPA, influenced by the Institute for Defense Analyses, increasingly viewed the general-purpose hydrocarbon fuel cell as a way to realize efficiencies within the supply chain. This brought the armed service's thinking into line with that of industry, for whom cost and durability mattered as much as performance. This coalition believed that a practical direct hydrocarbon fuel cell using the kinds of fuels common to the military-industrial supply base could be built relatively quickly and cheaply. By 1962, it had become clear to them that this could not be easily achieved, yet Project Lorraine was not immediately cancelled. The history of the U.S. terrestrial hydrocarbon fuel cell program in the 1960s accords well with Trevor Pinch's observation of how sociologists of technology and scientific knowledge have come to view experimentation and testing as a process of "argumentation and persuasion" rather than a means to confirm or refute techno-

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the various armed services, it used military rocket boosters to launch its first two classes of piloted spacecraft - Gemini relied particularly heavily on Air Force technical expertise - and the aerospace contractors that built its hardware generally derived most if not all of their revenue from sales of military equipment to the federal government.

scientific theories.[93] This lends insight into how Project Lorraine maintained its momentum. While both the Army and NASA deemed fuel cells worthy of underwriting high development costs, only the space agency had the resources to be able to live by the military credo of performance at any price.

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[93] Trevor Pinch, "'Testing-One, Two, Three…Testing!' Toward a Sociology of Testing," *Science, Technology & Human Values* 18, no. 1 (winter 1993): 29-30.

4 - Celestial Application, Commercial Anticipation: Bringing the Aerospace Fuel Cell Down to Earth

One of the attractions of the Seattle World's Fair in May of 1962 was the Second National Conference on Peaceful Uses of Space. Sponsored by NASA, the conference emphasized that the mission to land a man on the moon before the end of the decade, announced by President John F. Kennedy one year earlier, had far-reaching material benefits not only for the United States but for "all nations." A report prepared in support of the conference by the New York public relations firm Edward Gottlieb & Associates outlined a range of techniques and technologies devised for the space program that promised broader terrestrial use, including telecommunications, air travel, navigation and "amazing new sources of power," including the fuel cell. This "new" power source, noted the firm, was in "great demand" because spacecraft needed compact devices that could reliably supply electricity over long periods of time. The fuel cell, "like a car," would operate as long as fuel and oxidant were supplied. Soon, the report indicated, new compact fuel cells would be developed that would allow homes and businesses to generate their own heat and power, reducing dependence on the centralized gas and electricity grid and presenting a business opportunity as "huge" as space communications.[1]

Variations of this claim would be repeatedly made by NASA officials, the business media and politicians throughout the 1960s. In introducing fuel cell technology to the American consumer, Edward Gottlieb & Associates drew on assumptions then current in the U.S. fuel cell and space technology communities. The public relations firm's analogy between the familiar internal combustion engine and the fuel cell as a kind of electrochemical engine was reminiscent of Nathan W. Snyder's claim, made on behalf of the Institute for Defense Analyses three years earlier, that the electrical power source requirements of space, air, land and marine vehicles were virtually identical. Edward Gottlieb & Associates also implied that in developing the fuel cell for aerospace purposes, NASA would contribute to its adaptation in terrestrial applications, a concept known colloquially as "spin-off."

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[1] Edward Gottlieb & Associates, Ltd., "Civilian Dividends from Space Research: A Review of Some of the Peaceful Benefits from our Satellite Program, Now and in the Future," undated, Record Number 18530 IX: Technology Utilization, Addresses, Speeches, 28-29, NASA Headquarters Archive.

The precise nature of the space program's contribution to the development of fuel cell technology remains unclear. Scholars including Vernon Van Dyke, John M. Logsdon and the official NASA historian Eugene M. Emme have perceived NASA's influence mainly in political rather than scientific and technological terms, reflecting what Logsdon claimed to be the trend of the late 1960s and early 1970. To Logsdon, the more interesting question was how science and technology were employed to achieve national goals, rather than how space policy shaped science and technology.[2] Joan Lisa Bromberg's study of NASA's relationship with the aerospace industry is a notable example of an effort to gauge the space program's broader economic and technological impact.[3] However, Bromberg revealed little of how America's adventure in space influenced non-aerospace science, technology and commerce.

Similarly, scant effort has been devoted in the literature to exploring the space program's effect on fuel cell theory and technology. The fuel cell experts A.J. Appleby and F.R. Foulkes claim that NASA advanced fuel cell technology from a laboratory concept to a reliable multi-kilowatt power source, "enormously" contributing to the fields of electrochemistry and electrochemical engineering science in the process. They did not elaborate further.[4] There is, however, an interesting contrast in the positions of the federal government and certain of its private contactors regarding the space program's effects on fuel cell technology. While NASA expected to indirectly aid in the development of a terrestrial fuel cell, the Pratt & Whitney division of the United Aircraft Corporation (renamed the United Technologies Corporation in 1975), the agency's most important fuel cell supplier and the first to commercialize a terrestrial fuel cell design, denied that its involvement in space technology contributed in any meaningful way to its non-aerospace fuel cell business.

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[2] John M. Logsdon, *The Decision to Go to the Moon: Project Apollo and the National Interest* (Cambridge, MA: The MIT Press, 1970), ix.

[3] Joan Lisa Bromberg, *NASA and the Space Industry* (Baltimore: Johns Hopkins University Press, 1999).

As this chapter will demonstrate, NASA had neither the in-house capabilities nor the mandate to directly contribute to the development of terrestrial fuel cell technology, contrary to the suggestions of agency administrators. Nevertheless, its aerospace fuel cell program did have an important indirect effect on the subsequent conduct of commercial fuel cell research and development. As we shall see, NASA's contributions were not only material, as indicated by Appleby and Foulkes, but also ideological. The work of NASA and its contractors in adapting terrestrial fuel cells for use in spacecraft was widely perceived at the time by entrepreneurs, government administrators and the media as evidence that fuel cell technology in general was feasible. This raised hopes, particularly among ARPA managers, that hydrocarbon fuel cell projects would be similarly successful. The space agency's partnership with Pratt & Whitney also provided that company with invaluable experience in practical electrochemical engineering, allowing it to develop an infrastructure it would later exploit for commercial purposes. This positioned its parent company, United Aircraft/United Technologies Corporation, to become the leader in the nascent commercial fuel cell industry that began to emerge in the 1980s.

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[4] A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), 163.

Heavenly Handmaiden: NASA, Fuel Cells and the Final Frontier

From its inception, NASA's fuel cell program was bound up in expectations that the space program would benefit American science and technology. As the moon mission came under increasing criticism for absorbing a disproportionate amount of the nation's scientific and engineering resources, NASA's top leaders and their political supporters began to vigorously promote the idea that the space program would contribute as much to the national economy as to humanity's general fund of scientific knowledge. James Webb, the agency's second adminstrator, and Vice President Lyndon B. Johnson, the chair of the White House's National Aeronautics and Space Council and one of Webb's chief backers in Washington, began to claim that the space program would fulfill a much more expansive socio-economic role. They hoped NASA could combine the function of an institution of basic science with the industrial research laboratory: the agency would produce pure knowledge, techniques, materials and integrated technological systems that would facilitate urban development, communications, water and energy utilization and the life sciences.[5]

Kennedy's formal announcement on 25 May 1961 of the plan to place a man on the moon before the end of the decade entailed heightened rhetoric and organizational change within NASA. On 2 May, Webb sought to enlist the support of Kennedy's science advisor Jerome Wiesner, a moon mission skeptic, as a means of wooing the larger science community and deflecting criticism that NASA was concerned strictly with staging lurid "space spectaculars."[6] In November, Webb established a small Industrial Applications Office responsible for recording and monitoring technologies that were "spun-off" from the space program.[7] This bureau was later renamed the Office of Technology Utilization and its scope expanded so that it was charged with "translating" government research and development for the benefit of industrial engineering and production.[8]

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[5] W. Henry Lambright, *Powering Apollo: James E. Webb of NASA* (Baltimore: The Johns Hopkins Press, 1995), 110-111.

The promotion of the space program as an industrial cornucopia occurred at the highest political levels. At the Goddard Memorial Award Dinner in Washington, D.C. in March 1962, Lyndon Johnson claimed that the "real purpose" of the space program was not to "peek into the windows of heaven or to preen our national pride," but endow humanity "with new inventions and riches." The vice president understood the benefits of "space research" in two senses. On one level, it was a mobilization of national industrial resources akin to what had occurred during and after the Second World War, with immediate results: a bonanza of new consumer products; on another, "space research" was a kind of basic research project, yielding new materials "not known or named today." Johnson remarked that this effort then cost less annually than the $5 billion Americans spent each year on "face power, lipstick and nail polish." He promised that for "every nickel we put in, we get a dime back," comments widely repeated by pro-space media over the next few years.[9]

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[6] John M. Logsdon, *The Decision to go to the Moon: Project Apollo and the National Interest* (Cambridge, MA: The MIT Press, 1970), 119.

[7] Lambright, "The NASA-Industry-University Nexus: A Critical Alliance in the Development of Space Exploration," in *Exploring the Unknown: Selected Documents in the History of the U.S. Civilian Space Program: Volume II: External Relationships*, ed. John M. Logsdon (Washington, D.C.: NASA History Office, 1996), 418.

[8] Louis B.C. Fong, "The National Program of Technology Utilization: Third National Conference on the Peaceful Uses of Space, Chicago," 8 May 1963, Record Number 18530 IX: Technology Utilization, Commercial Application of Missile-Space Technology, 5, NASA Headquarters Archive.

Soon afterwards, the phraseology of the space technology "spin-off" began to appear frequently in the media and in the vocabulary of NASA bureaucrats. The fuel cell figured prominently in this campaign. In 1962, the editors of *Time* magazine published a book citing claims that of various spacecraft power sources, fuel cells offered "probably the broadest range" of application and were in the process of being developed for commercial use by the natural gas industry. Such devices were "already being carried over from the space industry" by General Electric and Westinghouse and promised to "revolutionize" the production and distribution of electricity on earth.[10] In October 1962, John E. Condon, the assistant director of NASA's Office of Reliability and Quality Assurance, told a gathering of the Mount Vernon, Ohio, Chamber of Commerce that the space program was expected to give rise to whole new *industries*, not simply individual pieces of technology, of which new power sources, especially fuel cells, was expected to be one.[11]

Five months later, James Dennison of NASA's Office of Technology Utilization addressed the annual meeting of the National Association of Business Economists in Cleveland in similar terms. Repeating what by then had become a standard NASA theme, Dennison framed the space program as a basic research program in which the specific outcomes and products could not be known in advance. The goal of the

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[9] Remarks of 16 March 1962, *Congressional Record*, 87th Cong. 2d sess., 1962, 108, No. 57 (12 April 1962), A2857-A2858. Johnson had also mentioned that Americans consumed $7.5 billion worth of cigars and cigarettes annually, but this was usually omitted in media reports.

[10] Gilbert Burke, "Hitching the Economy to the Infinite," in *The Space Industry: America's Newest Giant* (Englewood Cliffs, NJ: Prentice-Hall Inc., 1962), 96-97.

[11] John E. Condon, "Practical Values of Space Exploration," 10 October 1962, Record Number 18530 IX: Technology Utilization, Addresses, Speeches, 3-6, NASA Headquarters Archive.

Technology Utilization Program was to identify "incidental knowledge," new materials, processes, and techniques produced in the course of the program that had direct terrestrial relevance. These the administration was prepared to offer "at no charge to all comers, no strings attached." Among them was the fuel cell, "one of the most promising developments" in power sources. The space agency, along with the Department of Defense and industry, claimed Dennison, had done extensive research to make this technology commercially feasible. Experiments then underway to develop cheap, long-lived fuel cells capable of using piped natural gas promised a "revolution" in decentralized electricity production.[12]

It is important to note that NASA bureaucrats suggested that the agency's space activities were contributing to the development of commercial fuel cell technology both directly, in the sense of dedicated work to this end, and indirectly, through the production of processes, materials, and technologies that could be adapted for terrestrial use. This blurred distinctions between space and terrestrial applications, creating the impression that the fuel cell was on the verge of entering general use. In the early 1960s, however, NASA's research and development philosophy was geared almost entirely to its immediate goals, above all the Apollo project. In the weeks after the 12 April 1961 launch of *Vostok I*, the Soviet spacecraft that carried Yuri Gagarin as the first human being into space, the Kennedy administration determined that the United States needed a quick and dramatic space first to claim as its own. Landing a man on the moon by the end of the decade would be powerfully symbolic and promised a reasonable chance of success. In his inquiries with "space experts,"

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[12] NASA News Release, James T. Dennison, "Contributions of Aerospace Research to the Business Economy," 26 September 1963, Record Number 18530 IX: Technology Utilization, Addresses, Speeches, 12, NASA Headquarters Archive.

Johnson had been assured that such a mission required no technological breakthroughs but rather a development of "existing capabilities."[13] The immediate technological goal was to produce more powerful rocket boosters, a field in which the U.S. trailed the Soviet Union.[14]

As a result, "research" and "development" in the Apollo project were heavily weighted towards the development of proven propulsion technologies, with relatively little emphasis on basic research. Within NASA, responsibility for fuel cells was divided among two departments: the Office of Advanced Research and Technology (OART), later renamed the Office of Aeronautics and Space Technology (OAST), and the Office of Manned Space Flight. The OART/OAST comprised the field centers and personnel of the former National Advisory Committee for Aeronautics (NACA), which were absorbed into the new national space agency through the National Aeronautics and Space Act of 1958. The role of the NACA's three main facilities had been research and development in support of the aviation industry.[15] Following consolidation with NASA, the former NACA centres developed even broader responsibilities: they supplied research support both for NASA and the aviation and aerospace industries and worked to realize "practical benefits" in terrestrial applications from these space activities.[16]

The NASA fuel cell program originated in one of the former NACA centers. In 1958, Glennan established the Space Task Group (STG) at the Langley Research

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[13] Logsdon, *The Decision to go to the Moon: Project Apollo and the National Interest*, 98-99, 174.

[14] Lyndon Baines Johnson, *The Vantage Point: Perspectives of the Presidency, 1963-1969* (New York: Holt, Rinehart and Winston, 1971), 279-280.

[15] Joan Lisa Bromberg, *NASA and the Space Industry* (Baltimore: Johns Hopkins University Press, 1999), 2. The former NACA research centers were Ames, located in lower San Francisco Bay, Langley Field in Virginia and Lewis at the Cleveland Airport.

[16] Richard Hirsch and Joseph John Trento, *The National Aeronautics and Space Administration* (New York: Praeger Publishers, 1973), 66.

Center to manage Project Mercury, the first U.S. human-carrying spacecraft. The STG designed the Mercury capsule and developed the technical criteria for the Gemini and Apollo spacecraft, leaving the actual design for these latter vehicles to contractors. In late 1961, the STG was renamed the Manned Spacecraft Center and relocated to Houston under the aegis of the Office of Manned Space Flight. This quickly became most important single bureau within NASA, responsible for spacecraft and rocket boosters and commanding most of the agency's budget and personnel. The heart of the agency's fuel cell program was located in the Manned Space Center's Propulsion and Power Division, which controlled most of the funds available for fuel cell work. The center's tasks were largely administrative and involved funneling money to the fuel cell contractors, monitoring their progress and sharing responsibility with them for testing completed fuel cells at sophisticated facilities in White Sands, New Mexico.

The selection of fuel cell designs for piloted spacecraft was based purely on the perceptions of NASA planners of the technology's ability to meet their highly specialized needs, not adaptability for terrestrial purposes. Further, despite the reassurances of the "space experts" that the moon mission required no technological breakthrough, fuel cells were hardly a proven technology when NASA planners first began to study the possibility of using them in spacecraft in 1959. Consequently, the first five years of the aerospace fuel cell program were frustrating and tedious ones for NASA and its contractors as they rushed to prepare the technology for use in the Gemini and Apollo spacecraft. As in ARPA's terrestrial fuel cell program, the aerospace fuel cell effort was not simply a matter of applying knowledge of physical principles. Like the Department of Defense, NASA never developed a fuel cell master plan. Instead, decisions were made according to the changing requirements of the space program.

The subject of fuel cells as a possible spacecraft power source was broached during the meeting of the Goett Committee, a study group struck by NASA headquarters in April 1959 to study the technical options of a variety of space missions. Bruce T. Lundin of the Lewis Research Center observed that fuel cells were worth studying as a possible lightweight replacement for batteries to meet the unprecedented electrical power requirements of a moon spacecraft.[17] In assessing the capabilities of a number of power sources, the STG decided that fuel cells best suited the requirements of this mission on the criteria of light weight and reliability. As Union Carbide's Karl Kordesch had indicated to Bacon in 1957, the utility of fuel cells was limited by the weight of their fuel. For shorter missions, conventional batteries had the advantage. Very long missions posed greater problems. Only radioisotope thermoelectric generators had the ability to provide power for very long periods. But because these power sources produced electricity through the decay of radioactive material, heavy shielding was necessary if they were to be used in human-carrying spacecraft.

For missions of up to two to three weeks, however, STG/MSC planners believed fuel cells offered the ideal balance between power and weight, as well as a number of other advantages for space flight. Fuel cells allowed spacecraft designers to dispense with arrays of externally-mounted photovoltaic panels, a power source they feared might obstruct docking procedures. Using fuel cells embedded within the hull of the spacecraft, they believed, would allow for greater maneuverability, allowing non-solar oriented flight patterns useful for tracking stars to fix location.[18] Finally, planners hoped crews could consume the waste water produced by hydrogen-oxygen fuel cells, allowing further weight reductions. From NASA's perspective, fuel cells presented a "maximum in utility and a minimum of problems," promising the path of least engineering resistance.[19]

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[17] Courtney G. Brooks, James M. Grimwood and Loyd S. Swensen, Jr., *Chariots for Apollo: A History of Manned Lunar Spacecraft* (Washington, D.C.: National Aeronautics and Space Administration, 1979), 9.

While the Space Task Group was determined to build the Apollo spacecraft's electrical system around fuel cells, their enthusiasm was not universally shared within NASA. At least one deputy associate administrator warned D. Brainerd Holmes, the head of the agency's human space flight program, that fuel cells were not yet a proven technology. Thomas F. Dixon advised the STG to carefully review developments in the field. Though major strides had been made since 1957, he stated, fuel cells could not yet be considered close to "operational status."[20] The technology was fundamentally unlike other spacecraft power propulsion technologies such as liquid fuel rocket engines. Constructed of inert metals, such motors physically routed fuels into a combustion chamber and, in and of themselves, had long shelf lives. In contrast, fuel cells were volatile combinations of highly reactive substances that began to interact and physically change even before they were activated and fed fuel and oxidant, particularly if platinum was used as the catalyst.[21] Only arduous testing could reveal how these materials behaved over the long term. The process of actually building production fuel cells, a task monopolized by private contractors, in effect comprised the form of basic research known as engineering research, a protocol Pratt & Whitney and NASA developed by default and quite unexpectedly.

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[18] David Bell III and Fulton M. Plauché, *Apollo Experience Report: Power Generation System, NASA TN-D-7142* (Washington, D.C.: National Aeronautics and Space Administration, March, 1973), 2.
[19] Ernst M. Cohn, "Primary Hydrogen-Oxygen Fuel Cells for Space," text of presentation, June 1967, RN 13761: Propulsion, Auxiliary Power, Fuel Cells, 1961-1999, 2, NASA Headquarters Archive.
[20] Thomas F. Dixon to D. Brainerd Holmes, 12 December 1961, RN 13761: Propulsion, Auxiliary Power, Fuel Cells, 1961-1999, NASA Headquarters Archive.

Yet even before Kennedy had formally announced the moon mission and even as the STG drafted criteria for the Apollo auxiliary power unit, NASA had already determined that fuel cell technology was feasible and that Pratt & Whitney was the best candidate to supply it. This had as much to do with technopolitics as it did with technical merit. The National Aeronautics and Space Act of 1958 gave NASA the same procurement authority as stipulated in the Armed Services Procurement Act of 1947, allowing it to dispense with the traditional practice of competitive bidding and instead use "negotiation." This practice emerged during the Second World War as an emergency measure by which the federal government could develop a direct relationship with a selected contractor by fiat.[22] NASA headquarters developed such an arrangement with Pratt & Whitney. The parties agreed that the company would build a 250-watt pilot fuel cell that would serve as the basis for a full-size unit of between two to three kilowatts for the moon spacecraft.[23] Pratt & Whitney's successful development of this prototype led NASA to award the company the Apollo fuel cell contract in March 1962. For this role, the jet-engine maker planned to use the Bacon cell, the most advanced extant fuel cell technology.

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[21] John O'M. Bockris and Amulya K.N. Reddy, *Modern Electrochemistry 2B: Electrodics in Chemistry, Engineering, Biology and Environmental Science* 2nd ed. (New York: Kluwer Academic/Plenum Publishers, 2000), 1810-1815. Platinum's very high reactivity had long posed problems for fuel cell designers. For example, direct methanol fuel cells suffered from the problem of premature fuel oxidation at the platinum-laced cathode before the fuel could be consumed at the anode. In order to make the most efficient use of this catalyst, builders of phosphoric acid fuel cells dispersed it as a powder on a carbon "support" to provide the highest possible surface area. Writing in the late 1980s, A.J. Appleby and F.R. Foulkes noted that this structure tended to deteriorate over time: small crystals of platinum would coalesce or "sinter" into larger ones, decreasing the overall surface area of the catalyst and the efficiency of the fuel cell. They observed that this was the result of the corrosion of the carbon material and speculated that it might be caused by the catalytic effect of platinum on its own support structure. However, they were not sure and did not devote serious attention to the problem in *Fuel Cell Handbook* (368, 370).

[22] Lambright, "The NASA-Industry-University Nexus: A Critical Alliance in the Development of Space Exploration," in *Exploring the Unknown: Selected Documents in the History of the U.S. Civilian Space Program: Volume II: External Relationships*, 413.

At the same time, Allis-Chalmers, supported by NASA's Office of Advanced Research and Technology, was developing a rival version of the Bacon cell as a backup power source. Some specialists in the space agency would come to regard this as superior to the Pratt & Whitney model. Indeed, NASA overestimated Pratt & Whitney's ability to adapt a device originally developed for consumer applications for operation in spacecraft. The Bacon cell presented NASA and its contractors with a range of options relating to variations in pressure and electrolyte concentration, entailing a complicated series of trade-offs between high performance and reliability. Designing the technology with a civilian market in mind, Bacon had decided to use cheap nickel as the catalyst instead of costly platinum. The only way nickel became sufficiently reactive as a catalyst was by immersing it in potassium hydroxide operating at temperatures of above 100°C. Further experiments had revealed that raising the temperature to around 200°C in an electrolyte concentration of between 27 and 50 per cent increased performance without using more catalyst. In turn, this necessitated an increase in pressure to prevent the electrolyte from boiling. Bacon then discovered that increasing the pressure still further led to further improvements in performance. He then raised pressure well beyond what was needed to stabilize the electrolyte, reaching a maximum of 600 pounds per square inch or 41 atmospheres, later reduced to 400 pounds per square inch (27 atmospheres).[24]

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[23] Memorandum by Preston T. Maxwell, Aeronautical Research Engineer, Space Task Group, Langley Field, NASA, "Conference with Lewis Research Center Personnel to Discuss R&D Contract for Hydrogen-Oxygen Fuel Cell; Date of Conference, 25 April 1961," 27 April 1961, Record Number 16307, Program: Apollo, Location: Box 062-35, University of Houston-Clear Lake, Neumann Library.

Following the explosion of a Bacon pressure cell at the Leesona laboratories in 1961, Pratt & Whitney and NASA began to view the device as an unacceptable safety hazard in the aerospace application.[25] They wanted to abandon the pressure cell concept, yet reducing pressure reduced power. To compensate, Pratt & Whitney engineers increased the concentration of the electrolyte. This, however, brought new complications. Experiments conducted on two British-built Bacon cells in 1960 showed that the electrolyte concentration had important implications for the integrity of the physical structure of the fuel cell. At high concentrations, the electrolyte underwent phase change as temperature varied, solidifying as cells cooled after deactivation. This subjected the stack to physical damage. The thermal expansion that occurred as cells were activated and deactivated loosened the bracing structure within which they were stacked, which had to be periodically tightened.[26] As a result of these early tests, the Pratt & Whitney researcher in charge recommended lowering electrolyte concentrations. But the decision to proceed with a low-pressure device meant that a 30-percent aqueous solution of potassium hydroxide boiled at 204°C. To compensate, Pratt & Whitney decided to increase the electrolyte concentration to between 75 and 85 per cent and raise the operating temperature to 260°C. The resultant technology operated at only 3.4 atmospheres.[27] With the safety and power issues solved, this operating system was selected for the final production model, known as the PC-3A2.

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[24] Bernard J. Crowe, *Fuel Cells: A Survey* (Washington, D.C.: National Aeronautics and Space Administration, 1973), 8; F.T. Bacon and T.M. Fry, "Review Lecture: The Development and Practical Application of Fuel Cells," *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 334, no. 1599 (25 September 1973): 431-433; F.T. Bacon, "The Fuel Cell: Some Thoughts and Recollections," *Journal of the Electrochemical Society* 126, no. 1 (January 1979): 8C-9C. Efforts to operate at higher temperatures, pressures and potassium hydroxide concentrations created severe corrosion and leakage problems.

[25] F.T. Bacon, "Report on Visit to USA, 14-31 July, 1961 to see the Present State of Development of Fuel Cells," Papers and Correspondence of Francis Thomas Bacon, Section B, Research and Development, Energy Conversion Limited, Reports, B.672, 4, Churchill College Archives Centre, Cambridge University, England (hereafter cited as Bacon MS or TS).

[26] R.W. Fahle, "Short Memorandum Report No. 2940: An Investigation of the Performance of the British Bacon Fuel Cell," 31 August 1960, Bacon TS, Section B, Research and Development, Background Material, Fuel Cell Reports, 'Leesona-Moos and P&W,' B.1321, 3, 15.

These design changes combined to produce a highly corrosive and volatile operating environment, with important consequences for the lifetime of the fuel cell. The higher operating temperature and potassium hydroxide concentration also exacerbated the problem of thermal expansion that Pratt & Whitney first observed in 1960. Starting and deactivating the fuel cell were lengthy and delicate procedures to avoid damaging the electrodes as the concentrated electrolyte changed from a solid at room temperature to a molten liquid at operating temperature. One hazard arising from rapid deactivation and depressurization was a phenomenon known as "cold-popping," in which reactant gases were trapped in the cooling, hardening electrolyte. When the fuel cell was activated, the trapped gas formed a bubble between the electrode and the melting electrolyte, reducing the active electrode area and overall performance.[28] As a result, start-up could take hours, while shut-down required up to two days.[29] NASA had to ensure cells did not accumulate operating time exceeding

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[27] F.T. Bacon and T.M. Fry, "Review Lecture: The Development and Practical Application of Fuel Cells," *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 334, no. 1599 (25 September 1973): 440.

[28] Bell and Plauché, *Apollo Experience Report: Power Generation System*, 10.

[29] Crowe, 28. In fact, the fuel cell system was routinely activated much more than a "few hours" prior to the launch of crewed spacecraft. Between Apollos 7 to 11, systems were activated from a minimum of 35 hours (Apollo 7) to a maximum of 206 hours (Apollo 9) before launch: Apollo 7 (35 hours), Apollo 7 Mission Report, MSC-PA-R-68-15, December 1968, 5-39; Apollo 8 (48 hours), Apollo 8, Mission Report, MSC-PA-R-69-1, February 1969, 6-14; Apollo 9 (206 hours), Apollo 9 Mission

840 hours prior to launch.[30] The corrosive combination of high temperature and high electrolyte concentration created an altogether different and more difficult problem. When the fuel cell was under load, nickel ions leached from the cathode to the anode, where they accumulated and created an encrustation known as "dendrites," from its tree-like pattern. This nickel growth eventually bridged the electrolyte gap, creating a short circuit that damaged or destroyed the cell.[31]

Pratt & Whitney and NASA engineers appear to have designed early tests of the PC-3A2 simply as a means of confirming existing assumptions of its durability. Consequently, the unit was rushed into production before engineers fully understood how it behaved under realistic operating conditions over very long periods of time. It was a move NASA and the company would soon regret. While the early tests in 1960 had indicated some of the complications that would attend lowering pressure and increasing temperature and electrolyte concentration, Pratt & Whitney engineers did not anticipate the dendrite phenomenon. This was encountered well after the basic design had been frozen and subjected to longer and more rigorous tests.

The result was a fiasco for the contractor and the space agency. In early 1964, Pratt & Whitney delivered a batch of three prototype PC-3A2s to North American Aviation, the Apollo spacecraft prime contractor. NASA heralded the event as a

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Report, MSC-PA-R-69-2, May 1969, 8-13; Apollo 10 (57 hours), Apollo 10 Mission Report, MSC-00126, August 1969, 7-6; Apollo 11 (68 hours), Apollo 11 Mission Report, MSC-00171, November 1969, 8-4;

[30] Bell and Plauché, *Apollo Experience Report: Power Generation System*. 8.

[31] Bacon grew increasingly exasperated as the program stalled under the range of problems introduced by the decision to lower pressure. In an April 1964 letter to William Podolny, the head of Pratt & Whitney's fuel cell division, Bacon noted that all the various combinations of temperature, pressure, and electrolyte concentration that Pratt & Whitney was attempting to reconcile had been already been tried by the Cambridge laboratory. Bacon to W.M. Podolny, 28 April 1964, Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, 'Leesona-Moos and P&W,' B.1144.

"major milestone;" the Manned Spacecraft Center claimed that the fuel cells had been shipped after completing successful "acceptance tests" under simulated launch conditions.[32] The PC-3A2 was then rated for a lifetime of at least 400 hours or 16 full days of operation. However, all three prototypes soon developed severe problems, especially dendrite growth. One lasted for 112 hours before it failed, while the other two were severely damaged after being shut down and restarted. North American Aviation returned all three units to Pratt & Whitney for rebuilding.[33]

Pratt & Whitney's haste to place the PC-3A2 in production induced a major setback in the program. With many units already "in the pipeline" when failures began to occur, noted William Rice, the head of NASA's Power Generation Branch, costs skyrocketed.[34] Both contractor and the space agency appear to have been surprised by the fragility of the PC-3A2. It was not until early 1966 that a new, more rigorous and realistic testing program began at the Manned Space Center's White Sands facility in New Mexico.[35] This regimen, involving fuel cells integrated into the Apollo spacecraft's propulsion and power system, was extensive and costly, largely owing to the PC-3A2's unreliability. One engineer in the Power and Propulsion Division recalled that it had to be "babied;" units were discarded like a "flashlight battery" after accumulating 400 hours.[36] All told, these tests consumed as many as thirty full-sized production copies before the PC-3A2 was deemed fit for service in the Apollo spacecraft.[37]

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[32] "First Fuel Cell Delivery Called Apollo Milestone," *Roundup: NASA Manned Spacecraft Center* Vol. 3, No. 6, 8 January 1964, 1.

[33] Harvey J. Schwartz, "Batteries and Fuel Cells," in *Space Power Program Review for Office of Advanced Research and Technology, Lewis Research Center July 13-14 1964, Volume II: Presentations*, RN 13717: Space Power Review, 7, NASA Headquarters Archive.

[34] William E. Rice, interview by Rebecca Wright, NASA Johnson Space Center Oral History Project, 18 March 2004, 7-8.

[35] "Apollo Power System In White Sands Test," *Roundup: NASA Manned Spacecraft Center* Vol. 5, No. 7, 21 January 1966, 8.

The fruit of almost 35 years of research, the Bacon cell in the form of the PC-3A2 eventually performed well, providing electricity and water for astronauts in eleven Apollo spacecraft flights. In this configuration, however, the Bacon cell contradicted the original assumptions that distinguished fuel cells from conventional batteries in the first place: electrode invariance and long life. In immediate technological terms, Pratt & Whitney and NASA transformed a device designed for the commercial market in Britain into a highly specialized, costly and short-lived technology that was difficult to operate. The ERA and the NRDC spent tens of thousands of pounds developing the Bacon cell. In contrast, the space agency devoted over $100 million in adapting it for the aerospace role.[38]

Like the U.S. Army's hydrazine fuel cell, the final version of the Bacon cell was essentially an expensive disposable primary battery that, outside of NASA's celestial sphere of patronage, was as much a technological orphan as the original device had been in Britain. Of the various organizations that had sponsored the Bacon cell over the years, only NASA was prepared to subsidize the costs of supplying hydrogen. Despite the program's expensive and protracted development, the fuel question was relatively much simpler where a handful of spacecraft were concerned. Large-scale commercial applications were far more complex, demanding wholesale renovations to the fuel production and supply infrastructure. Not surprisingly, the fuel cell community viewed the PC-3A2 as a dead end in electrochemical energy conversion well before the device was used in the first piloted mission in Apollo 7 in December 1968. Pratt & Whitney's success validated Bacon's life work, yet the technology seemed to have little future potential. The point was aptly though unintentionally conveyed in a congratulatory letter from Pratt & Whitney on the occasion of the successful flight of Apollo 8 informing Bacon that his "grandchildren have performed flawlessly…and went to their fiery Valhalla as heroes."[39]

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[36] William Simon, interview by John Mauer, "Oral History with Bill Simon about Early Space Shuttle development," 22 March 1984, Record Number 15557, Program: Shuttle, Location: SHU-INT2, 4-5, University of Houston-Clear Lake, Neumann Library.
[37] Rice interview by Wright, 11.
[38] Williams, 11.

There is, however, another aspect of the history of the Bacon cell that remains to be considered. This is the legacy to electrochemical science and fuel cell research and development of the years of effort to make the Bacon cell work in spacecraft. Although Pratt & Whitney had made its name in the field with the PC-3A2, the company was emphatic that the device had no commercial value whatever outside its immediate use in the Apollo spacecraft. What was more, it was loath to credit the space program with any role at all in its efforts to develop commercial acidic hydrocarbon fuel cells.

As will shortly be discussed, however, making the Bacon cell work in space had important material and ideological consequences for NASA and Pratt & Whitney. For the former, it was an example of technological virtuosity and a tantalizing taste of what the space agency might contribute to the national economy. For the latter, developing the PC-3A2 had important consequences for its technology base and its aspirations as a maker of commercial fuel cells. This played a crucial role in the construction of what Leesona's Harry Oswin referred to as the "energy conversion empire" in the United States.[40] Before turning to these matters, it is necessary to explore NASA's in-house fuel cell effort in light of the agency's public claims to have directly contributed to advancing commercial fuel cell technology.

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[39] J.R. Foley to F.T. Bacon, 3 January 1969, Bacon TS, Section B, Research and Development, Laboratories and Sponsors, 'Leesona-Moos and P&W,' B.1148.

Spinning Spin-Off: The Fuel Cell as a Space Dividend

Throughout the aerospace fuel cell program, agency officials and the media continued to suggest that the effort would spawn a terrestrial "spin-off." An important assumption attending this idea was that the space agency was a major supporter of research and development. The science and technology policy analyst Harvey Brooks has stated that along with the Department of Defense and the Atomic Energy Commission, NASA was one of the "big three" federal research and development agencies. Together, they accounted for some 93 per cent of federal research and development expenditures, which in turn constituted some 70 per cent of all investment in research and development by 1963. The atomic energy and space agencies in particular had the "more explicit" goal of fostering commercial "spin-offs" from their research programs.[41]

Brooks has also observed that the linear mode of research and development has proved fruitful in circumstances where the product was completely novel, where product differentiation was unnecessary, when the developer had much larger research and development resources than its competitors and was producing for a protected market where performance was valued over cost and where the volume of products was small. These conditions were present in the weapons, telecommunications, nuclear, computer and electronics industries, at least in the early stages of the Cold War.[42] These factors also applied to NASA's fuel cell program. However, the space agency did not have a conventional linear research and development relationship with its industrial contractors and had no philosophical justification to conduct extensive in-house research. Generally, NASA spent much less on university research than the Department of Defense, particularly after the moon missions were completed.[43] As we have seen, the space agency was almost entirely absorbed with sponsoring the development of existing technologies that would facilitate the moon mission as quickly as possible. To this end, practically all of NASA's funds went directly to contractors concerned solely with building hardware, a policy initiated by Glennan and continued by Webb, leaving few resources for in-house research and development.[44]

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[40] Harry Oswin to F.T. Bacon, 29 October 1968, Bacon TS, Section B, Research and Development, Laboratories and Sponsors, 'Leesona-Moos and P&W,' B.1147.

[41] Harvey Brooks, "The Evolution of U.S. Science Policy," in *Technology, R&D, and the Economy*, eds. Bruce L.R. Smith and Claude E. Barfield (Washington, D.C: The Brookings Institution and American Enterprise Institute, 1996), 21- 23.

These institutional protocols and the unique challenges posed in developing aerospace fuel cell technologies meant little of the highly specialized work conducted by the contractors was directly relevant for the development of commercial terrestrial fuel cells. This left NASA's in-house fuel cell research and development program as the only source of a direct "spin-off." This capability lay in the Office of Advanced Research and Technology, the administrator of the former NACA research centers. The OART's Lewis facility at the Cleveland airport had a dedicated fuel cell department that was part of its larger space power program. But the OART lacked a coherent fuel cell research and development philosophy, a situation that stemmed in part from the ambiguous position the research centers occupied in the NASA hierarchy. They inherited NACA's role of serving the commercial aviation industry, which had been transforming into an aerospace industry since the mid-1950s. The research centers were additionally responsible for discovering "practical benefits" from space *and* conducting long-term research in support of future NASA missions.

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[42] Ibid., 22.

[43] Bruce L.R. Smith, *American Science Policy Since World War II* (Washington, D.C.: The Brookings Institution, 1990), 56, 84.

[44] James E. Webb, *National Aeronautics and Space Administration, Fifth Semi-Annual Report to Congress* (Washington, D.C.: United States Government Printing Office, 1962), iii-iv. Webb noted that between 1 October 1960 and 30 June 1961, the proportion of the agency's funds transferred to private organizations had risen from 80 to 92 cents on the dollar.

As we have seen, NASA's practice was to turn over virtually all responsibility for technology development, and such research and development as there was scope for, to the private sector. Where the agency's aerospace fuel cell program was concerned, the vast bulk of effort was devoted to near-term manned missions, programs in which the engineering was done by private contractors and management supplied by the Manned Space Center. What was more, in the mid-1960s, NASA had identified few future spacecraft missions that clearly called for fuel cell power. That being so, there was little justification for an in-house fuel cell program. Consequently, the Lewis space fuel cell program effectively supported neither existing nor long-term space programs. A NASA review of this program in April 1963 found that it lacked goals and a clear sense of purpose within the agency's institutional hierarchy. The review determined that there was insufficient in-house research on fuel cells and batteries. It called for effort to be divided on a short and long-term basis, recommending more resources for basic research and support for the human spacecraft projects.[45] In particular, the review suggested the Lewis Research Center could play a role in diagnosing and evaluating problems with the ion-exchange membrane technology General Electric was developing for the Gemini mission.

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[45] H.J. Schwartz, "Chemical Systems" in *Space Power Review*, 18-20 April 1963, Summary, Record Number 13716: Space Power Review, NASA Headquarters Archive.

The 1963 space power review was far less certain as to which future power requirements longer-term basic research would serve. The difficulty was that for the time being, NASA had fixed its agenda in human space flight, forcing the panel to speculate on the roles a future fuel cell might play. Conventional fuel cells that required their own fuel supplies limited the choice of spacecraft to types that had mission profiles similar to NASA's first generation of piloted craft. Such power sources were suitable for missions longer than several days, after which the weight of the necessary batteries became prohibitive, but no longer than several weeks, after which the requisite fuel became too heavy.

This ruled out fuel cells as a power source for deep space human or robot craft. Concepts included a fuel cell that could consume the "tank residuals" of a hydrazine-powered rocket, but the joint panel's real hope was for a regenerative cell reconstituting its reaction products using photovoltaic electricity. Lewis' fuel cell manager believed such a system would be useful mainly for a geosynchronous earth satellite because its 24-hour orbit offered a much longer period of solar exposure and electricity generation than the 90-minute low-earth satellite orbit. The greatest potential application of such a system, planners believed, was as a moonbase powerplant.[46]

A subsequent review conducted 15 months later reported major improvements in the fuel cell program. OART officials cited the investment of $75 million in fuel cell work for Gemini and Apollo, an effort that reflected the "concentrated efforts of the contractors and the Lewis team."[47] This was misleading, for it failed to distinguish between the two separate fuel cell efforts underway at NASA. These funds had been channeled through the Manned Space Center's fuel cell program and disbursed to the private contractors, not to OART's Lewis space power program. Fuel cell work in this division had not in fact been appreciably expanded in support of existing fuel cell technology programs, as the review had suggested. What was more, the "good progress" observed in electrochemical technologies referred mainly to batteries, not fuel cells. On a funding basis, the latter remained Lewis' lowest space power priority. Of a total budget of almost $83 million in Fiscal Year 1964, the research center allocated only six contracts worth a mere $2 million for fuel cells. Electrochemical technology had a far lower priority than either solar or nuclear technologies, which received $10.9 and $67 million respectively in Fiscal Year 1964. Lewis had no full-scale fuel cell projects of any type. Such work as did occur in the field was limited to improving components of existing fuel cell concepts, particularly the ion exchange membrane type, to obtain better durability. This was not directly related to the two major technology projects then underway for NASA human spacecraft. Lewis devoted only 16 professional technicians to fuel cells, compared with 174 and 69 in the nuclear and solar fields respectively. For Fiscal Year 1965, Lewis even proposed to slash fuel cell funding by almost half to $1.1 million.[48]

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[46] Ibid., 4.

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[47] H.J. Schwartz, "Battery and Fuel Cell Program," in *Space Power Program Review for Office of Advanced Research and Technology, Volume I: Summary*, 13-14 July 1964, Record Number 13717, Space Power Review, 8, NASA Headquarters Archive.

[48] Bernard Lubarksy, "Overall View of the Lewis Power Program," in *Space Power Program Review for Office of Advanced Research and Technology: Volume II: Presentations*, 13-14 July 1964, Record Number 13717, Space Power Review, 6, NASA Headquarters Archive.

The bulk of the OART's effort in fuel cells was concentrated not at Lewis but at the Marshall Space Flight Center in Huntsville, Alabama. This was an unusual program in several respects. One of three field centers under the jurisdiction of the Office of Manned Space Flight, the Marshall facility was best known for testing and modifying the big booster rockets that fired the Apollo spacecraft into orbit. It did not host long-term research and development in the same sense as the OART research centers. Furthermore, the fuel cell program technically directed at Marshall using OART money was based not on an advanced new model for future NASA missions but rather an improved Bacon-style cell designed by Allis-Chalmers. Begun in 1962, this project became a joint effort with the Office of Manned Space Flight in 1964. With the Pratt & Whitney program then experiencing severe setbacks, the Office of Manned Space Flight was then considering the Allis-Chalmers fuel cell as a backup system for the Apollo mission.[49] By 1967, Allis-Chalmers had accumulated 19,000 hours of testing on 21 laboratory fuel cells and had built and tested eight full-size two-kilowatt units.[50] In late 1968, NASA awarded the company a $3.5 million contract to produce four fuel cell stacks for qualification testing.[51] Some agency managers believed the Allis-Chalmers design was superior to Pratt & Whitney's PC-3A2. It employed an electrolyte at a lower concentration than the Pratt & Whitney model and contained it within an asbestos mesh, obviating some of the thermal expansion and corrosion problems attending the use of strong potassium hydroxide solution. Operating at around 87°C instead of 204°C, the Allis-Chalmers asbestos matrix Bacon cell weighed 185 pounds, 55 pounds less than the PC-3A2, and, at 2800 watts, produced more than twice the power.[52]

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[49] Schwartz, "Battery and Fuel Cell Program," in *Space Power Program Review, Volume I*, 8.

[50] "Transcript of the Briefing on NASA Space Power and Electric Propulsion Programs," 24, 27 April 1967, Record Number 13761: Propulsion, Auxiliary Power, Fuel Cells, 1961-1999, 30-31, NASA Headquarters Archive.

[51] "Allis-Chalmers Gets AAP Fuel Cell Work," *Roundup: NASA Manned Spacecraft Center*, Vol. 8, No. 4, 6 December 1968, 1.

In short, NASA's fuel cell program was conservative and focused almost entirely on primary and backup systems for ongoing human spacecraft programs. What was more, it had been decided at the agency's highest levels that its requirements for fuel cells in the foreseeable future could be met by improving existing technologies. In 1966, George Mueller, the associate administrator for Manned Space Flight, vetoed plans for a new 90-day fuel cell system proposed by Robert Gilruth, the director of the Manned Spacecraft Center. Mueller believed that the potential of the Pratt & Whitney and Allis-Chalmers systems for human missions of between 28-56 days had not been fully exploited.[53] Agency administrators were satisfied that the Bacon cell design, a technology dating back to the late 1930s, could serve their needs well into the future. Consequently, they devoted almost no resources to advanced fuel cell research and development, let alone commercial terrestrial fuel cell work.

Nevertheless, NASA continued to claim throughout the 1960s that its fuel cell program would pay terrestrial dividends. Privately, some of its managers were skeptical. The views of Ernst Cohn on this issue are particularly interesting for what they reveal of the ways political pressure to justify the space program's social utility shaped NASA's presentation of the fuel cell "facts" to scientific and technology communities. As the director of electrochemical systems at the Space Power and Electrical Division of OART, Cohn was in an unusual position. As a former member of the Army Ordnance Corps and the Army Research Office, he had played an important role in launching Project Lorraine. Cohn's decision to transfer to NASA in the early 1960s placed him at the administrative head of a relatively small and unimportant department that had little technical involvement in a research and development program dominated by the Office of Manned Space Flight.

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[52] Ibid., 1.

[53] George E. Mueller to Robert R. Gilruth, 17 August 1966, Record Number 13761: Propulsion, Auxiliary Power, Fuel Cells, 1961-1999, NASA Headquarters Archive.

Cohn's chief role seems to have been less as a researcher than a liaison with the larger science and technology communities. His message varied according to the audience. In his addresses to scientific societies and in his internal reports, Cohn presented greatly contrasting visions of NASA's fuel cell program and its relevance for terrestrial applications. For example, the bulk of Cohn's presentation at the Army-sponsored Seventeenth Annual Power Sources Conference of May 1963 was largely speculative. He focused mainly on the power-to-weight tradeoffs represented by future space power sources including the various regenerative types. However, Cohn noted that biological fuel cells consuming gases produced by human waste or the metabolism of the human body, a concept under consideration for deep space journeys, had also been proposed as a power source for a pacemaker.[54]

Cohn was much bolder in his presentation to the American Chemical Society that September. This time, biocells figured more prominently as a prominent space "spin-off." These technologies had, Cohn claimed, "captured the public's imagination." They might even be a solution to the water pollution crisis, running on hydrogen produced by microbes consuming raw sewage. More importantly, he stated that virtually all of the information produced in NASA's aerospace fuel cell programs would be equally valid for terrestrial fuel cells, a position that recalled the original assumptions of the Institute for Defense Analyses and ARPA in drafting Project Lorraine. Cohn concluded that in solving the problems of fuel cells in the space power role, NASA hoped to advance the technology in ways that would benefit the national economy.[55]

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[54] Ernst M. Cohn, "Space Applications," in *Proceedings: Seventeenth Annual Power Sources Conference, 21-23 May 1963* (Red Bank, NJ: PSC Publications Committee, 1963), 86.

These were major claims to make at the annual conference of one of the oldest and most important of American scientific societies. They were amplified both by virtue of their placement as the very first item in the published version of the proceedings as well as by the fact that Cohn spoke on behalf of NASA, not the OART and its Space Power program. But in his contribution to the Kennedy administration's Interdepartmental Energy Study drafted several weeks earlier, Cohn painted a much more complex picture of the state of fuel cell development. He observed the growing interest in the technology in the United States, noting that in Fiscal Year 1963, industry spent $10 million and government $8 million on research and development. The space agency contributed an additional $38 million on fuel cells for Apollo and Gemini, $28 for the former and $10 million for the latter. Cohn predicted that fuel cells would have many terrestrial uses and promised a potential solution to the problem of air pollution by reducing fossil fuel emissions. He also spoke of using "conventional fuels" in fuel cells, repeating assumptions then shared by ARPA managers and Army researchers. Costs were currently much too high but, claimed Cohn, would drop when demand warranted "mass production."[56]

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[55] Cohn, "NASA's Fuel Cell Program," in *Fuel Cell Systems: Symposia sponsored by the Division of Fuel Chemistry at the 145th and 146th Meetings of the American Chemical Society, New York, Sept. 12-13, 1963, Philadelphia, Pa., April 6-7, 1964* (Washington, D.C.: American Chemical Society, 1965), 8.

Yet Cohn also observed that fuel cells were an embryonic technology of which little was known. The main reason there was such broad commercial and government interest was because it was widely believed that fuel cells were not subject to the limitations on heat engine efficiency, even under ideal conditions, as dictated by the Carnot cycle. In theory, fuel cells could attain efficiencies as high as 60 per cent, compared to the 40 per cent typical for commercial power plants. The problem with such assumptions, Cohn indicated, was a gap between theory and what was possible given the engineering of the day. His analysis reflected the fact that by late 1963, researchers had only just begun to attempt stacking small laboratory devices into multi-cell prototypes. Because most testing had hitherto been on single cells, maintenance costs were largely unknown, as were details on longevity and reliability. These observations presaged the comments of General Electric's Research Laboratory team at the American Chemical Society conference in New York that September. Though systems engineering and life-testing of full-scale fuel cells had "barely begun," it was likely, noted Cohn, that failure modes for stacks of fuel cells would be far different than for single cells. The development of aerospace fuel cells for the Gemini and Apollo spacecraft, the first fuel cells to be put to practical use, would certainly provide valuable experience. But he doubted if this would prove relevant for terrestrial applications considering that the aerospace models were designed to use pure hydrogen and oxygen over a period of only two weeks at most.[57] Nowhere in the report did Cohn make an explicit claim of "spinning-off" a terrestrial version of a space fuel cell.

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[56] Cohn, "Interdepartmental Energy Study: Chemical and Biochemical Fuel Cells," 19 August 1963, Record Number 13761: Propulsion: Auxiliary Power: Fuel Cells, 1961-1999, 13, 24-33, NASA Headquarters Archive.

As for biological fuel cells, said Cohn, power densities would have to be increased "100-fold" before the technology could compete with existing electrochemical technologies. In fact, he stated, biocells were not expected to play a major role where alternate forms of power were available.[58] Ameliorating water pollution could be better served by non-fuel cell solutions, he added. Cohn also cast doubt on the cost estimates cited in *Fuel Cells: Power For the Future*, the influential text of the Harvard Business School graduate students and the source of a number of optimistic assessments of fuel cell technology. Cohn believed their claim of capital costs of between $7.50 to $10 per kilowatt was far too low. The gasoline internal combustion engines of the time produced about 12 kilowatts per cubic foot and cost about $3 per kilowatt, while the extant fuel cells typically produced between one to three kilowatts per cubic foot. Actual costs for commercial fuel cells, Cohn noted, were likely to range from around $50 per kilowatt for short-lived devices up to $150 to $300 per kilowatt for longer-lived equipment. By way of comparison, General Electric's Gemini fuel cell cost as high as $47,500 per kilowatt. Finally, he noted that the so-called indirect solution, the use of an external hydrocarbon reformer, itself entailed a complicated refining process that would add expense and detract from efficiency.[59] This prediction came to pass after 1965, when problems with hydrocarbon reformer-fuel cells made the hydrazine system seem an attractive alternative to Army planners.

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[57] Ibid., 15-16.
[58] Ibid., 30.
[59] Ibid., 13-16.

Cohn's presentation at the American Chemical Society in the fall of 1963 glossed these difficulties. He gave the impression that NASA was indeed fulfilling its promises of "spin-off," following the Office of Technology Utilization's line that dividends from space were a byproduct, not the primary object, of the agency's efforts. The agency, the press and industry maintained this view well into the 1970s.

Making Space Pay: NASA, General Electric and the Dual-Use Fuel Cell

Of the firms developing fuel cell technology in the 1960s, General Electric was perhaps the greatest proponent of "spin-off." The company was supremely confident that it would be first to bring a commercial product to the marketplace. While the company failed to complete the development of the direct propane/methane hydrocarbon cell begun with ARPA support and demonstrated to some fanfare in April 1963, it believed the ion-exchange cell being prepared for the Gemini spacecraft had much greater potential. General Electric mounted the largest media effort promoting fuel cells of any private company, becoming one of the foremost propagandists of the concept of the "dual-use" fuel cell.

The ion exchange membrane fuel cell originated in the realization of General Electric researchers L.W. Niedrach and W.T. Grubb that polymer membranes used as water softeners were excellent conductors of ions and might be used as electrolytes in fuel cells operating at temperatures of between 50°C to 100°C.[60] Niedrach and Grubb applied an acidic polymer membrane in a fuel cell in 1955 and in 1959, General Electric began to adapt the technology for military and aerospace applications at its

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[60] W.T. Grubb, "Ion-Exchange Batteries," in *Proceedings: Eleventh Annual Battery Research and Development Conference, 22-23 May 1957* (Fort Monmouth, NJ: Battery Conference Committee, 1957), 5; M.L. Perry and T.F. Fuller, "A Historical Perspective of Fuel Cell Technology in the 20th Century," *Journal of the Electrochemical Society* 149, no. 7 (2002): S60.

Lynn, Massachusetts facility. The company believed membrane fuels cells avoided many of the problems associated with liquid electrolytes types. A solid membrane obviated the danger of a liquid electrolyte "flooding" the electrode, making possible the combination of electrode and electrolyte in a single assembly. This allowed designers to dispense with the heavy porous electrodes required by liquid electrolyte systems and develop lighter and more compact stacks of cells. Finally, General Electric's acidic membrane rejected carbon dioxide and, as a result, could operate on air instead of pure oxygen. This also made possible the use of hydrocarbon fuel, at least in theory.

In many ways, General Electric's experience in developing the membrane fuel cell for the Gemini spacecraft mirrored the difficulties encountered by Pratt & Whitney in the Apollo program. Approved in December 1961, six months after the announcement of Apollo, Gemini had been conceived as a means to accumulate experience in the space flight procedures of rendezvous and docking that would be employed during the moon mission. NASA managers also saw Gemini as an opportunity to prove a number of new technologies including fuel cells. As in the case of Pratt & Whitney, the space agency did not choose the General Electric design as the result of a competitive bid. According to the official NASA history of the Gemini project, the decision had been the prerogative of a single mid-ranking official named Robert Cohen. Originally, the Manned Space Center planned to use batteries in the spacecraft. But as mission length, and the weight of batteries, was increased, Cohen selected General Electric's membrane fuel cell as the primary power source following his personal survey of existing power source options. His rationale was that the design was lighter, simpler, and at least as well developed as competing designs.[61]

General Electric was characteristically enthusiastic. In early 1962, its officials claimed that single test cells had demonstrated a lifetime of 2000 hours or 83 days of continual operation, well above the two weeks of the longest planned Gemini mission.[62] Prime contractor McDonnell Aircraft also favored the membrane fuel cell and in March of 1962, it let a $9 million subcontract to General Electric. The power system consisted of six stacks of 32 cells each, producing a total of two kilowatts at maximum output. As with Pratt & Whitney, the decision to proceed with General Electric's fuel cell technology had not been without controversy. A dissenting report submitted by an official from the Office of Manned Space Flight following an informal visit to the Lynn plant in March 1962 concluded that General Electric's fuel cell program was unprepared to meet the Gemini program's strict deadlines, citing a lack of personnel and slow progress on a completely unproven design.[63]

The program soon ran into major difficulties. Like Pratt & Whitney, General Electric began to build production fuel cells before subjecting them to long-term tests, with similar results. Part of the problem was that while General Electric had completed construction of its production facility at Lynn in late 1962, work on the ten-station test stand lagged, as we have seen. The installation was not fully operational until early 1964.[64] The fuel cell also experienced major technical difficulties relating to the polymer membrane that only became apparent over time. The membrane was extremely sensitive and degraded in almost all conditions, especially at higher temperatures. Moreover, it offered high electrical resistance, inhibiting the flow of current.[65] It was also prone to dehydration and cracking, allowing hydrogen and oxygen to seep through and directly react, leading to fires and the possibility of explosion.[66] Finally, it was susceptible to contamination from materials used in other parts of the cell.[67]

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[61] Barton C. Hacker and James M. Grimwood, *On the Shoulders of Titans: A History of Project Gemini, NASA SP-4203* (Washington, D.C.: National Aeronautics and Space Administration, 1977), 103. Cohen faced criticism when the program became mired in difficulties. However, in a 1967 interview, Cohen claimed the final decision to use the ion-exchange fuel cell in Gemini spacecraft was made by James Chamberlin, the director of the Gemini project; Robert Cohen, interview by Peter J. Voorzimmer, 21 February 1967, Record Number 030076: Oral History Interviews, NASA Headquarters Archive. The endorsement of the GE fuel cell by McDonnell Aircraft must also be considered as a factor in the OMSF's decision-making chain of command.

[62] E.A. Oster, "Ion Exchange Membrane Fuel Cells," in *Proceedings: Sixteenth Annual Power Sources Conference, 22-24 May 1962* (Red Bank, NJ: PSC Publications Committee, 1962), 23.

[63] Ibid., 104.

As with Pratt & Whitney, failures struck production models. Problems immediately arose when, in the summer and fall of 1963, General Electric shifted emphasis from engineering and development to production. Progress was slowed by faulty parts and materials provided by subcontractors and by delays in their replacement.[68] In late November, persistent engineering and manufacturing difficulties forced General Electric to shut down its production line.[69] As the program fell behind schedule, there were signs it might be abandoned altogether. NASA's Gemini Project Office was sufficiently concerned that it asked McDonnell to study the possibility of replacing the fuel cell with conventional batteries on spacecraft conducting the longer rendezvous missions. It was not simply a matter of the reliability of the fuel cell stack itself but its functionality when integrated into the spacecraft's electrical and cooling system. Although laboratory tests in 1963 indicted the fuel cell stack had a lifetime of around 600 hours, modifications to the spacecraft's cooling system increased the power source's operating temperature, drastically reducing its useful life to between 150 and 200 hours.[70] In response, General Electric reorganized its Lynn plant and brought in a new manager, Roy Mushrush, with sweeping new powers to use whatever resources were necessary to turn the operation around. [71]

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[64] General Electric, "Saturated Hydrocarbon Fuel Cell Program, Quarterly Letter Report Number 5, January 1 1964-March 31 1964," Box 2, AO 247-General Electric, DA-44-009-ENG-4909, 1, National Archives and Record Administration II.

[65] Ernst M. Cohn, "The Growth of Fuel Cell Systems," August 1965, Record Number 13761: Propulsion, Auxiliary Power: Fuel Cells, 1961-1999, 5-7, NASA Headquarters Archive.

[66] William Simon, interview by John Mauer, "Oral History with Bill Simon about Early Space Shuttle Development," 22 March 1984, Record Number 15557, Program: Shuttle, Location: SHU-INT2, 7, University of Houston-Clear Lake, Neumann Library.

[67] Grimwood and Hacker, *On the Shoulders of Titans: A History of Project Gemini*, 149.

[68] James C. Grimwood and Barton C. Hacker, *Project Gemini Technology and Operations: A Chronology, NASA SP-4002* (Washington, D.C.: National Aeronautics and Space Administration, 1969), 104.

[69] Grimwood and Hacker, *On the Shoulders of Titans*, 178.

Even as difficulties with the fuel cell system persisted throughout 1964 and 1965, General Electric's public relations bureau developed a language of technological boosterism that elided the actual capabilities of the fuel cell in space applications with its potential in projected terrestrial roles, while avoiding explicit claims to this effect. The company released a brochure in 1964 lauding both its achievements in space fuel cell technology and its successful electro-oxidation of hydrocarbons, presumably as part of Project Lorraine. The promotional literature acknowledged that while practical applications of this type of cell "may be years away," the fact that it could operate on "readily available fuels" was of major significance. The brochure concluded by claiming that fuel cells were "already in production." Despite the hyperbole, the applications General Electric envisioned were highly specialized and included fork lift trucks, golf carts and scuba diver sleds.[72] This indicated that before the fuel cell could be competitive in the most lucrative market, the passenger automobile, costs had to be cut and reliability increased.

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[70] Grimwood and Hacker, *Project Gemini Technology and Operations*, 116-117.
[71] Grimwood and Hacker, *On the Shoulders of Titans*, 178.
[72] Direct Energy Conversion Operation, General Electric, "Fuel Cells for Power in Space," NAM/NASM 1673, Cat. No. 1966-0646 and 0647, p. 0008, National Air and Space Museum Archive.

Later that year, General Electric began to plan a major campaign promoting the aerospace membrane fuel cell. It selected the Smithsonian Institution's National Air Museum (NAM), one of the nation's most august organizations, as the stage to spotlight its latest technological advance, the first production Gemini fuel cell stack to accumulate 1000 hours of ground operation. The company planned to donate this unit for temporary exhibition at the NAM. Choreographing the event as a lavish media spectacular, General Electric solicited the help of Democratic Senator Edward M. Kennedy of Massachusetts to officiate the hand-over as a representative of a state in which the firm had major investments.[73]

Such promotional zealotry raised eyebrows among NAM managers. General Electric's plan to display the technology before it had been proven in an actual Gemini spacecraft mission struck Frederick C. Durant III, the museum's assistant director of astronautics, as imprudent. On paying a visit to the Lynn plant in March of 1965, he had observed that the company was "wild" to "make a big do" of the event. In his report to NAM Director S. Paul Johnston, Durant noted that he had advised General Electric officials to delay any exhibition until after the fuel cell had flown in a successful space flight.[74] Such caution proved well-founded. During the first operational test of the fuel cell in the remotely controlled and pilotless Gemini II spacecraft in January, the power source malfunctioned and was shut down before the rocket lifted off.[75] NASA and McDonnell decided the fuel cell was still too unreliable to be used in the first two piloted Gemini spacecraft, opting instead for conventional batteries in launches in March and June. Lynn manager Roy Mushrush reluctantly accepted Durant's advice; nevertheless, he insisted that the 1000-hour ground test was significant in and of itself because it represented a major advance in the development of "practical fuel cell power" in general.[76] For General Electric, the fact that the fuel cell had functioned for an extended period in a controlled terrestrial setting overshadowed its failure in Gemini II and its exclusion from Geminis III and IV.

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[73] Chester J. Civin to Edward M. Kennedy, 30 December 1964, NAM/NASM 1673, Cat. No. 1966-0646 and 0647, p. 0002, National Air and Space Museum Archive.

[74] Frederick C. Durant III to S. Paul Johnston, undated, NAM/NASM 1673, Cat. No. 1966-0646 and 0647, p. 0021-0023, National Air and Space Museum Archive.

The flight of a fuel cell system on the eight-day Gemini V mission on 21 August represented the first successful practical application of a General Electric fuel cell, an occasion the company lost little time in trying to exploit. In a press conference held less than two weeks later, its officials announced that the ion-exchange fuel cell would be developed for commercial use. General Electric portrayed the event as a major milestone in the history of electrical power. Arthur M. Bueche, a company vice-president for research, declared that fuel cells were the first "practical major power source to be developed since atomic energy."[77] The phrase was repeated in the Smithsonian Institution's official press release announcing a 10-day exhibit in January 1966 of a 1100- hour production unit "identical" to the one that had served on Gemini VII.[78] The *New York Times* quoted company officials promising that the power source would be commercially available in early 1966 for remote television cameras, golf carts, forklifts and scuba diver sleds.[79]

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[75] Grimwood and Hacker, *Project Gemini Technology and Operations: A Chronology*, 179.

[76] R.S. Mushrush to F.C. Durant, 10 May 1965, NAM/NASM 1673, Cat. No. 1966-0646 and 0647, p. 0020, National Air and Space Museum Archive.

[77] "Commercial Uses of Fuel Cell Seen: GE Will Market Device it Built for Gemini 5," *The New York Times*, 2 September 1965, p.38.

[78] Smithsonian Institution Press Release, "Smithsonian To Get General Electric Fuel-Cell Power Source; Identical With Those Used in the Successful Gemini VII Mission," 10 January 1966, NAM/NASM 1673, Cat. No. 1966-0646 and 0647, p.0028-0029, National Air and Space Museum Archive.

Such applications, however, were hardly commensurate with Bueche's grandiloquent rhetoric. What was more, the performance of the fuel cell in Gemini V had been far from ideal. The prime contractor's report noted that the system displayed "unusual modes of operation," and planners subsequently used conventional batteries for the two-day Gemini VI mission. General Electric fuel cells were used for the remaining six flights, performing tolerably well, although this was indicative more of the degree of redundancy that had been built into the system than the intrinsic reliability of the fuel cell stacks themselves. Individual stacks failed in Geminis XI and XII, though the remaining ones were able to supply sufficient power.[80] Indeed, planners never gained sufficient confidence in the General Electric fuel cell to use it as the spacecraft's sole source of electricity. All Geminis used batteries as the primary power system.[81] In a sense, this was a repudiation of the fuel cell, for it had been rationalized precisely as a battery replacement to save weight. Cohen, the NASA manager whose recommendation had helped pave the way for the use of the membrane fuel cell, later opined that batteries were far more reliable and easier to use and had fuel cells "beat hands down."[82]

For NASA, no less than for General Electric, the success of aerospace fuel cells was important, for it would allow the agency to bolster its claim that the space program was devolving important technologies into the larger economy. By the late 1960s, the fuel cell had become "perhaps most prominently publicized" of the space program's contributions to the private economy, according to General Electric promotional literature.[83] A steady stream of rhetoric to this effect continued to emanate from the media, politicians, NASA personalities and General Electric's public relations office well into the early 1970s. The language of fuel cell boosterism was refined for popular consumption by no less a personage than Wernher von Braun, the former Nazi scientist and latter-day NASA rocket-builder. In a 1967 address to members of the Foreign Investors Council at the Kennedy-Space Center, von Braun observed that fuel cells were a key technology for NASA, having already seen service in the Gemini spacecraft. Such devices, he claimed, would be of "tremendous interest" for many industries outside the aerospace sector and were an "almost classic" example of a Space Age technology spin-off. One company had already built a tractor, while others were "playing" with the idea of a reversible fuel cell for domestic use: plug it in at night and it would electrolyze water into pure hydrogen using off-peak electricity. In the morning, homeowners could start up the fuel cell and enjoy silent power all day long. One might even be able to plug in one's fuel cell electric automobile at night in the same way. Not only would this be a "very economical" way to drive, held von Braun, it might also be a solution to the "smog problem."[84]

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[79] "Commercial Uses of Fuel Cell Seen: GE Will Market Device it Built for Gemini 5," *The New York Times*, 2 September 1965, p.38.

[80] P.W. Malik and G.A. Souris, *NASA Contractor Report CR-1106: Project Gemini: A Technical Summary; Prepared by McDonnell Douglas* (Washington, D.C.: National Aeronautics and Space Administration, 1968), 2, 50, 56-59.

[81] Malik and Souris, *NASA Contractor Report CR-1106*, 50, 56-59.

[82] Robert Cohen, interview by Peter J. Voorzimmer, 21 February 1967, Record Number 030076: Oral History Interviews, 1, NASA Headquarters Archive.

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[83] General Electric, *Benefits From Space*, March 1969, Record Number 06911: NASA Space Spin-Offs, 8, NASA Headquarters Archive.

[84] Wernher von Braun to Members of Foreign Investors Council, 15 October 1967, Wernher von Braun Papers, Box 127, File 9, United States Space and Rocket Center, Huntsville, Alabama.

General Electric continued to claim a dual-use commercial potential for its aerospace ion-exchange membrane fuel cell into the late 1960s, well after the federal government and practically all other companies involved in terrestrial hydrocarbon fuel cell research and development had abandoned such work. The company kept its hopes alive through NASA contracts for exploratory research on a fuel cell for the post-Apollo reusable space plane then in development. Perhaps recalling the trouble that had resulted from negotiating contracts directly with the two perceived technology leaders during the first piloted spacecraft programs, NASA decided to foster "competition" between the leading candidates, providing development funding for newer versions of the existing aerospace fuel cell designs of General Electric, Pratt & Whitney and Allis-Chalmers.[85] With the support of the Manned Spacecraft Center and the Office of Advanced Research and Technology (renamed the Office of Aeronautics and Space Technology), General Electric finally solved the problem of membrane dehydration and cracking, developing a method of humidifying the hydrogen fuel and oxidant before they were pumped into the cells.[86]

For Cohn, these trends epitomized the shallowness of NASA's fuel cell program. On the one hand, a tough, realistic and long-term regimen of "engineering research" was necessary to improve existing systems. But such a program was only just getting started by mid-1967. The lifetime of fully assembled stacks often proved only a fraction of that of individual cells, not necessarily owing to shoddy construction but instead because slight variations in cell manufacture had effects which only became apparent during long-term operation. As Cohn observed, many of the problems with fuel cell systems were actually of the "engineering 'detail' variety," involving auxiliary systems that had been contaminated with impurities or improperly manufactured.[87]On the other hand, Cohn believed that the rush to build usable aerospace fuel cells led contractors to opt to improve conservative designs and ignore more daring ideas. With the OAST/OART preoccupied with the Allis-Chalmers asbestos-matrix Bacon cell, Cohn's complaint echoed the IDA scientist Nathan W. Snyder's criticism of ARPA's space power program in 1960. Bolder approaches, held Cohn, would benefit both aerospace and commercial terrestrial fuel cells.[88]

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[85] William E. Rice, interview by Rebecca Wright, NASA Johnson Space Center Oral History Project, 18 March 2004, 7.

[86] William Simon, interview by John Mauer, "Oral History with Bill Simon about Early Space Shuttle Development," 22 March 1984, Record Number 15557, Program: Shuttle, Location: SHU-INT2, 7, University of Houston-Clear Lake, Neumann Library.

Such boldness became increasingly unlikely as the space agency began to downsize its human space flight program in the late 1960s and early 1970s. Not only was the pool of government money for fuel cells shrinking, but NASA decided to select a single technology supplier. The competition for the Space Shuttle fuel cell contract had been close, according to Cohn, but was won by Pratt & Whitney in 1971 on the basis of "better engineering," even though the General Electric membrane fuel cell itself was "very good."[89] In November 1972, NASA shut down the fuel cell power section of the Propulsion and Power Division at the Manned Spacecraft Center.[90] By 1974, Cohn believed that with Pratt & Whitney's new Shuttle fuel cell supplying NASA's space power needs well into the foreseeable future, the days of in-house fuel cell research and development at the administration were numbered.[91] The only other application for an aerospace fuel cell on the horizon was the space station, a one-off project requiring only a handful of fuel cell stacks.

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[87] Ernst M. Cohn to F.T. Bacon, 8 April 1974, Bacon MS, Section G, Correspondence, Fuel Cell Correspondence, G.149.

[88] Ernst M. Cohn, "Primary Hydrogen-Oxygen Fuel Cells For Space," June 1967, Record Number 13761: Propulsion, Auxiliary Power: Fuel Cells, 1961-1999, 7-12, NASA Headquarters Archive.

[89] Bacon notes on meeting with Cohn, 17 July 1974, Bacon MS, Section G, Correspondence, Fuel Cell Correspondence, G.150.

[90] Manned Spacecraft Center Announcement, "Organizational Changes to the Propulsion and Power Division Engineering and Development Directorate," 14 November 1972, Record Number 137246, Report Number 72-176, Program: Center, Location: GR 1015, University of Houston-Clear Lake, Neumann Library.

By the late 1970s, General Electric's fuel cell program had come to a crossroads. In the early 1960s, the company had been one of the most ardent proponents of the hydrocarbon fuel cell. Together with ARPA, it believed the technology would revolutionize power production. The failure of Project Lorraine left the ion exchange membrane concept as the company's best hope for a dual-use fuel cell. Unlike Pratt & Whitney, General Electric tried to adapt a common design for aerospace and terrestrial purposes. While the membrane fuel cell was successfully developed at tremendous cost for use in spacecraft, its dependence on pure hydrogen ruled it out of all but a handful of niche applications. Ultimately, General Electric found that the costs of developing these far outweighed the benefits.

NASA and Commercial Fuel Cell Development

How should the legacy of NASA's involvement in fuel cell research and development be understood? The scholarship on the history of fuel cells has generally assumed that the space program advanced this power source technology in general, tending not to distinguish between aerospace and terrestrial fuel cell technology, direct and indirect benefits or ideological and material benefits. As we have seen, there is no question that the aerospace fuel cell program, the first successful application of the technology outside the laboratory, inspired work on terrestrial fuel cells. In April 1962, the American Academy of Arts and Sciences, aided by a NASA grant, struck a panel known as the Committee on Space Efforts and Society charged with studying the social effects of the space program. Raymond A. Bauer, the committee's chair, observed that people tended to develop a belief in the potential applicability of space technology in terrestrial roles mainly through analogy rather than demonstrable evidence of similarity.[92] This accurately describes ARPA's interpretation of NASA's aerospace fuel cell program.

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[91] Bacon notes on meeting with Cohn, 17 July 1974, Bacon MS, Section G, Correspondence, Fuel Cell Correspondence, G.150.

The material legacy of the space program to fuel cell technology is more complex. Where aerospace fuel cell technology is concerned, this chapter has demonstrated that NASA's in-house efforts directly contributed to the development of aerospace fuel cell technology through long-term testing of production models, as well as some applied research on the General Electric ion-exchange membrane. It has also been established that NASA did not directly advance terrestrial fuel cell technology. However, as will shortly be demonstrated, NASA's massive funding of the aerospace fuel cell programs of the private contractors indirectly created the basis for a commercial fuel cell industry, providing the resources, experience and motive necessary to enable certain of them to develop terrestrial fuel cell technology.

Part of the difficulty in understanding how the space program influenced the development of fuel cell technology has been the imprecision with which NASA officials and their political supporters employed the term "spin-off." They referred to this in two senses: the harder claim was that the fuel cell itself had been developed to serve the space program; the softer one held that aerospace represented the first meaningful application of the technology. Either way, NASA officials claimed that aerospace fuel cells had or would shortly contribute to the development of terrestrial fuel cell technology.

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[92] Raymond A. Bauer, *Second-Order Consequences: A Methodological Essay on the Impact of Technology* (Cambridge, MA: The MIT Press, 1969), 170.

There is no question that fuel cell technology in general was not a genuine space "spin-off," having existed in conceptual form since the mid-nineteenth century. If anything, a kind of reverse spin-off had occurred, because existing terrestrial designs had been adapted for non-terrestrial purposes.[93] As re-designed for spacecraft, they were costly and short-lived devices. Consequently, only *aerospace* fuel cells can be said to be a direct product of the space program. Further, NASA and the two largest fuel cell contractors had fundamentally different interpretations of the notion of "spin-off." Although both hoped to commercialize fuel cell technology, only General Electric actively worked to develop a common design for aerospace and commercial terrestrial purposes. Though its officials promoted the membrane fuel cell as a space "spin-off," the technology had originally been developed for terrestrial use in a 200-watt hydrogen-fueled "backpack" system built for the Army.[94] General Electric was simply trying to exploit the favorable public relations resulting from the far more dramatic and prestigious use of the technology in spacecraft. While NASA had contributed to solving one of the membrane fuel cell's main reverse salients, this did not translate into commercial success for General Electric. What was more, improvements to this fuel cell technology after the late 1960s owed much less to the efforts of NASA or General Electric than to efficient new polymer membranes introduced by the Du Pont and Dow chemical companies.[95]

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[93] The term seems to have been first used in 1974 by a graduate student at George Washington University's Department of Science, Technology and Public Policy named Jim Maloney. Maloney employed it in a paper written under the aegis of the Smithsonian Institution's National Air and Space Museum as background research for an exhibit devoted to the socio-economic benefits of air and space flight intended for the inauguration of the NASM's new facility as part of the bicentennial celebrations of 1976. Maloney correctly observed that the fuel cells developed for the space program had been adapted from existing terrestrial designs. Basing his analysis on interviews with Pratt & Whitney executives, Maloney denied that the transfer of existing fuel cell technology to space applications, what he termed "reverse spin-off," had *any* consequences for the broader course of terrestrial fuel cell research and development. He claimed that the federal government's support of aerospace fuel cell work had in fact *inhibited* the development of a commercial fuel cell, though he did not address "reverse spin-off" in any depth; Jim Maloney, unpublished essay, "Fuel Cells: A Case Study of Benefits from Flight," 15 May 1974, Record Unit 348, Box 3: United Aircraft, 36, Smithsonian Institution Archive, Washington, D.C.

[94] U.S. Army Signal Research and Development Laboratory, "Fuel Cells for Radar Set AN/TPS-26 (XN-1)," *Research and Development Summary* 8, no. 1, 1 January 1961.

NASA, Pratt & Whitney and the Phosphoric Acid Fuel Cell

The issue of fuel cell "spin-off" in the relationship between NASA and Pratt & Whitney is more complicated. While the space agency had claimed for years that its aerospace fuel cell program had benefited terrestrial fuel cell technology, Pratt & Whitney was ambivalent about the consequences of its participation in this effort. The key issue was NASA's role in the development of the company's phosphoric acid fuel cell. Capable of using "dirty" hydrogen reformed from hydrocarbons, the type became the first terrestrial fuel cell to reach the market in the early 1990s.

The earliest versions of this technology were developed as part of TARGET (Team To Advance Research for Gas Energy Transformation), the world's largest commercial fuel cell program in the late 1960s and early 1970s. Begun in 1967, this $90 million nine-year joint venture between Pratt & Whitney and American, Canadian and Japanese gas utilities yielded several dozen stationary natural gas-fed fuel cell generators for field trials. The project illustrates Callon's maxim of how fuel cell research and development is driven by alliances among actors with disparate techno-social interests. It had origins in the end of the Apollo program and the advent of the reusable Space Shuttle. With orders for alkaline aerospace fuel cells peaking in the mid-1960s and expected to decline thereafter, Pratt & Whitney decided that its best commercial opportunity lay in developing a fuel cell for the gas utilities.[96]

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[95] Charles Stone and Anne E. Morrison, "From curiosity to 'power to change the world®,'" *Solid State Ionics* 152-153 (2002): 3-4.

For the latter, the program was an opportunity to break into the electricity market. Reasoning that less energy was lost in gas pipelines than in high-tension power lines over long distances, the gas utilities saw the phosphoric fuel cell as a decentralized power generator that could be integrated into the pipeline grid and installed in homes and businesses, a concept known as distributed generation. This, the gas utilities believed, would allow them to compete with the big central stations of the electrical utilities. The resulting partnership spawned the natural gas-fuelled phosphoric acid utility generator as the sole fuel cell application with commercial potential in the late 1960s.

TARGET was built around the PC-11, Pratt & Whitney's first prototype phosphoric acid power plant. Between 1971 and 1973, 65 of these 12.5-kilowatt units were built and distributed among the gas utilities for long-term trials.[97] At $100,000 per kilowatt, the PC-11 was far too costly to be commercially viable.[98] However, TARGET had a number of important consequences for the future practice of commercial fuel cell research and development. It allowed Pratt & Whitney to gain valuable experience operating phosphoric acid fuel cells as utility generators. It also provided a model for the alternate fuel cell-based energy order that came to be known as the "hydrogen economy," of which more will be said in Chapter Five. Finally, the TARGET partners used environmental justifications as a marketing tactic, appealing to quality of life issues in a period when large-scale nuclear, hydroelectric and fossil-fuelled energy and transportation technologies were under increasing scrutiny from environmental and public interest groups.[99] This tactic would be widely emulated by fuel cell developers in the 1990s.

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[96] T.M. Fry, "Visit of Mr. Podolny," 21 August 1970, Bacon TS, Section B, Research and Development, Background Material, 'Miscellaneous,' B.1350, 2.

[97] Joseph M. King and Michael J. O'Day, "Applying Fuel Cell Experience To Sustainable Power Products," *Journal of Power Sources* 86 (2000): 17.

[98] A.J. Appleby, "Issues in Fuel Cell Commercialization," *Journal of Power Sources* 69 (1996): 156.

Pratt & Whitney and some fuel cell analysts have understood TARGET as purely a private sector venture.[100] Although the company had emerged from the Space Race as the world's leading fuel cell developer through its monopolization of what remained of the aerospace market and its role in TARGET, it never made a serious effort to adapt its aerospace fuel cell technology for terrestrial purposes. What was more, Pratt & Whitney sharply distinguished between its aerospace and commercial fuel cell programs in its public statements. Unlike General Electric, it never made spin-off claims. In an interview published in *Aviation Week & Space Technology* in 1973, William Podolny, the chief of Pratt & Whitney's fuel cell division, denied that the space program had benefited the company's efforts to develop a commercial terrestrial fuel cell.[101]

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[99] Pratt & Whitney promotional literature published in 1972 described the phosphoric acid fuel cell as "an efficient, pollution-free source of electricity" that would "conserve our natural resources;" see "A New Generation of Electric Generating Systems," Pratt & Whitney Aircraft, S 3462, May 1972, Bacon TS, Section B, Research and Development, Background Material, 'Miscellaneous,' B.1352. In a paper drafted for a meeting of the Institute of Electrical and Electronics Engineers in the winter of 1972, Pratt & Whitney engineers claimed that fuel cell utility generators would address public concerns with the effects of the existing power grid including air pollution, thermal pollution of water, aesthetics, radioactive emissions, siting and transmission right-of-way; see W.J. Lueckel, L.G. Eklund and S.H. Law, "Fuel Cells for Dispersed Power Generation," a paper recommended by the IEEE Power Generation Committee of the IEEE Power Engineering Society for presentation at the IEEE Winter Meeting, New York, NY, January 30-February 4, 1972, paper No. T72 235-5, p.1-6, The Institute of Electrical and Electronics Engineers, 1.

[100] Appleby and Foulkes have characterized this project as a lifeline for fuel cell research and development following the federal government's withdrawal from the field in the early 1970s; see *Fuel Cell Handbook*, 13.

[101] Clark Martin, "Apollo Spurred Commercial Fuel Cell," *Aviation Week & Space Technology*, 1 January 1973, 56.

NASA and its political supporters believed otherwise. In an address to the Twentieth Century Club of Hartford in November 1968, George E. Mueller, chief of NASA's manned space flight program, stated that the agency's efforts in "activating" the fuel cell from dormancy for use in space had contributed to TARGET's efforts to develop fuel cells for home use. Despite having personally delimited the scope of the space agency's fuel cell work to the refining of existing highly specialized fuel cells for near-term space missions two years previously, Mueller believed that NASA deserved a share of the credit when Pratt & Whitney began production of commercial fuel cells in Hartford.[102]

Similar language was employed in the campaign of the House Committee on Science and Astronautics to promote the benefits of the space program in the late 1960s and early 1970s. In May 1970, committee member Louis Frey, Republican of Florida, presented a report in Congress identifying direct and indirect spin-off benefits. Undertaken by Frey's district Astronautics and Aeronautics Advisory Committee, composed of chief executives from the nation's leading space industry firms, the report repeated Mueller's phraseology, claiming NASA had "activated" the fuel cell from a long "dormancy" to power spacecraft. The report then linked these efforts to TARGET, noting that 28 gas utilities were spending $20 million to "adapt" the fuel cell for home power units.[103]

A House committee inquiry on NASA's role in fuel cell development in August 1971 elicited a more explicit response that further bolstered the notion of spin-off.

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[102] George E. Mueller, 11 November 1968, Record Number 012978: Inventions from Space Program, NASA Headquarters Archive.

[103] Extension of remarks, 30 April 1970, *Congressional Record*, 91st Cong. 2d sess., 1970, 116, No. 69 (1 May 1970), E3785, E3788.

The agency's Office of Legislative Affairs (OLA) claimed that NASA's investment in fuel cells for Gemini and Apollo, some $170 million, comprised more than 70 per cent of the total national research and development effort on fuel cells during the 1960s. Only recently had industrial investment exceeded that of the federal government. Furthermore, claimed the OLA, the private sector's fuel cell design and engineering database, workforce and facilities had been developed almost entirely as a result of the space program.[104]

What, then, did it mean to adapt fuel cell technology developed in the context of the space program for terrestrial applications? How are we to account for the divergent views of NASA managers, the House Committee on Science and Astronautics, the aerospace industry and Pratt & Whitney? While NASA and its main fuel cell contractor had a symbiotic relationship, they also had distinct interests in fuel cell technology. The space agency was interested mainly in procuring high-performance hardware; Pratt & Whitney, on the other hand, was motivated solely by profit and was naturally concerned to protect its intellectual property. The company was extremely reluctant to share information on commercial fuel cells. For this reason, Pratt & Whitney would not sponsor cooperative research of the kind performed at the Battelle Institute. This concern to preserve commercial advantage soured working relations between Pratt & Whitney and Energy Conversion Limited, the British licenser of the Bacon and Chambers fuel cell patents. Relations became especially fractious when the British team tried to learn what the Americans were up to with hydrocarbon-fuelled acid fuel cell technology.[105]

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[104] Gerald J. Mossinghoff, Deputy Assistant Administrator (Policy), Office of Legislative Affairs, to Carl Swartz, Minority Staff, Committee on Science and Astronautics, House of Representatives, 18 August 1971, Record Number 013761: Propulsion: Auxiliary Systems: Fuel Cells, 1, NASA Headquarters Archive.

Proprietary rights were a constant source of tension between Pratt & Whitney and NASA. The space agency's statutory policy on patents resembled that of the Atomic Energy Commission, claiming public ownership of inventions developed under contract to the government.[106] This did not matter so much to Pratt & Whitney where the Bacon cell was concerned, for the technology had been licensed from the NRDC/ECL and few harbored visions of its terrestrial applicability. It did, however, became an issue during the Shuttle program. NASA's Ernst Cohn had criticized the company during the design competition for using the cheapest possible materials, leading to poor performance, and for its unwillingness to generate new innovations, which would have less patent protection.[107]

This concern for intellectual ownership informed a strangely equivocal attitude on the part of Pratt & Whitney towards the commercial fuel cell technology that it developed concurrently with its aerospace fuel cells, an ambivalence that stemmed from the changing nature of the company's relationship with its federal patron in the late 1960s and early 1970s, as well as failed expectations regarding the civilian fuel cell market. Pratt & Whitney was adamant that NASA had had nothing to do with the development of commercial acid fuel cell technology, yet blamed its lack of commercial success on the space agency. By early 1973, Pratt & Whitney was growing disenchanted with TARGET as it faced serious technical, financial and regulatory obstacles. The company publicly disavowed the claims of some of the utilities that it would be producing phosphoric acid fuel cells at a rate of 100,000 a year by 1975.[108] With TARGET behind schedule and over budget, Podolny lashed out at NASA. In the *Aviation Week & Space Technology* interview, he accused the space agency of forcing Pratt & Whitney into the unprofitable commercial fuel cell field. He claimed that the government had given the company little option but to go this route in an effort to recover its investments in personnel and infrastructure made as a result of the aerospace fuel cell program. Podolny recounted that Pratt & Whitney began investigating in fuel cell technology in 1958 on the assumption that it would allow the company to diversify its product line and reduce its dependence on military aviation. As a result, the firm had committed to a five-year commercial fuel cell program in 1960. But by the end of that year, said Podolny, the company had determined that the technical and economic obstacles were too formidable to continue. Pratt & Whitney had been preparing to abandon its commercial fuel cell effort, Podolny claimed, when NASA stepped forward with the cost-shared contract for the 250-watt demonstration unit, which then led to the Apollo contract in March 1962. This extended Pratt & Whitney's involvement in fuel cells for another five years, a period during which it had assembled a dedicated electrochemical engineering workforce and built a specialized manufacturing facility.

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[105] G.T. Rogers, "Visit to Pratt & Whitney, Hartford Connecticut, Institute of Gas Technology and Argonne National Laboratory," July 1971, Bacon TS, Section F, Visits and Conferences, 'Visit to USA', F.28, 3-4.

[106] Public Law 85-568, 85th Congress, 2d sess. (29 July 1958), *The National Aeronautics and Space Act of 1958*, 9-10.

[107] Ernst M. Cohn to William E. Rice, "Meeting with Pratt & Whitney on October 21, 1971," 26 October 1971, Record Number 4764, Report Number RPP, Program: Shuttle, Location 007-14, University of Houston-Clear Lake, Neumann Library, Houston, Texas.

It was the attempt to make use of these resources after the Apollo program was completed, said Podolny, that "trapped" the firm into trying to make a commercial business of fuel cells. There were, he insisted, no similarities between aerospace and commercial fuel cells, either in terms of their operating systems or production techniques, and thus no connection between NASA and Pratt & Whitney's commercial fuel cell work. All that he would allow was that the federal government had provided "a meaningful base for exploring commercial activities."[109] In effect, Podolny claimed that government intervention, through NASA, had altered the normal operation of the market. Had it not been for the space agency's aerospace contracts, Pratt & Whitney would have abandoned fuel cells altogether. Despite Podolny's efforts to diminish federal involvement in the company's commercial fuel cell program, however, blaming NASA for Pratt & Whitney's difficulties in this sector implied that the government had indeed played some role in the development of this technology after all. This impression was conveyed in the *Aviation Week & Space Technology* article, which ran under the headline of "Apollo Spurred Commercial Fuel Cell."

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[108] "Fuel Cells: Production by '75? Politics Could Prove Utilization Snag," *Energy Digest*, 22 July 1971, 102.

Pratt & Whitney was determined to efface such linkages. In a series of interviews conducted in early 1974 under the aegis of the Smithsonian Institution, Podolny and other Pratt & Whitney officials did not repeat the "trapped" argument. Part of a research project sponsored by the Smithsonian's National Air and Space Museum, the interviews were held in support of an exhibit it was preparing for the NASM's new facility then under construction in Washington as part of the 1976 bicentennial celebrations. Entitled "Benefits From Flight," the exhibit was designed to showcase the economic and social effects of the aerospace industry, in short, to promote and legitimize the concept of "spin-off."

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[109] Clark Martin, "Apollo Spurred Commercial Fuel Cell," *Aviation Week & Space Technology*, 1 January 1973, 56.

The Smithsonian Institution's resulting study of fuel cells, based heavily on the Pratt & Whitney interviews, concluded that the Apollo program played absolutely no role in spurring development of commercial fuel cells.[110] In these interviews, Podolny drew back from his earlier suggestion that the aerospace fuel cell program had made some contribution to Pratt & Whitney's commercial fuel cell program by expanding its knowledge and material base. His new position was that NASA had simply given Pratt & Whitney the *incentive* to consider the fuel cell as a commercial possibility. All that NASA had provided was encouragement and resources sufficient to allow the company to train a "few people" in fuel cell technology. William Lueckel, Pratt & Whitney's program manager for electrical utilities, went even further, categorically denying that there was any connection whatsoever between NASA funding and the company's commercial fuel cell work.[111]

In fact, Pratt & Whitney's collective memory of its relationship with NASA in fuel cell research and development was inconsistent. Although Podolny claimed that the company had entered the fuel cell field in 1958 strictly with commercial aspirations in mind, there is little evidence that much work to this end was done at that time. Pratt & Whitney's activities in the late 1950s and early 1960s seem to have focused almost entirely on military and aerospace applications during a period when its most important fuel cell technology was the Bacon cell. A company list of fuel cell milestones cited no notable achievements before January 1962, when it completed tests of the pilot fuel cell for NASA.[112] During his visit to the Pratt & Whitney facility at East Hartford in July 1961, Bacon reported that the company's fuel cell efforts were devoted mainly to military purposes and to the Apollo spacecraft, a project with strong military-industrial connections. That such work was well underway five months before the successful demonstration of the 250-watt unit that won Pratt & Whitney the Apollo contract and eight months prior to the formal award of this contract further undermines Podolny's claims because it suggests that the company was confident it would find a market in the military-aerospace sphere.

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[110] Jim Maloney, unpublished essay, "Fuel Cells: A Case Study of Benefits from Flight," 15 May 1974, Record Unit 348, Box 3: United Aircraft, 29, Smithsonian Institution Archive, Washington, D.C.
[111] Ibid., 30.

There is also evidence that Pratt & Whitney had intended from the outset to use government military-aerospace fuel cell contracts as a springboard to a commercial product. Bacon noted that not only was no serious work on commercial fuel cells underway at Pratt & Whitney in mid-1961 but that any future work in that field was contingent on the successful development of military and quasi-military aerospace fuel cells.[113] This was reinforced by the conclusions of an Energy Conversion Limited fact-finding team dispatched to the United States in January 1962. By this time, it was widely known in the international fuel cell community that Pratt & Whitney was the leading contender for the Apollo contract and that NASA's specifications put the Bacon cell "right outside any commercial use." The ECL team regarded the Apollo contract as the single most important development in the fuel cell field in the immediate future and believed that if Pratt & Whitney claimed it, the company's electrochemical engineering resources would be fully committed.[114]

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[112] "News, Pratt & Whitney Aircraft: Pratt & Whitney Aircraft Fuel Cell History," Bacon TS, Section B, Research and Development, Background Material, 'Miscellaneous,' B.1353, 1.

[113] F.T. Bacon, "Report on Visit to USA, from July 14-31 1961, to See the Present State of Development of Fuel Cells," Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.672, 9.

The ECL team also learned that in the event Pratt & Whitney won the Apollo contract, it planned to divide its fuel cell program into separate aerospace and commercial branches, insulating the public and private aspects of its business and shielding commercial research from the company's competitors.[115] This strongly suggests that a formal commercial fuel cell project did not then exist at Pratt & Whitney and that its viability was dependent upon a major infusion of resources from NASA. Furthermore, although Pratt & Whitney's fuel cell program quickly expanded after the company won the Apollo contract in March 1962, it does not appear to have been reorganized into completely hermetic commercial and non-commercial units. It is true that funds for alkaline aerospace fuel cell systems came almost exclusively from government contracts, while support for commercial acid fuel cells was provided mainly by private gas companies. However, Pratt & Whitney appears to have been unable to completely insulate the money streams flowing into its private and public projects, resulting in a certain degree of pooling of knowledge and technology produced with government and industry funds. An ECL report of 1964 indicated that the firm's fuel cell program then consisted of three departments: two devoted to systems for the Apollo project and a third, known as the Advanced Power Systems group, dedicated to commercial technology. The largest of the three divisions with some 800 workers (compared to 700 in the Apollo program), the

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[114] J.N. Haresnape, E.A. Shipley, G.H. Townend and K.E.V. Willis, "Report of the Technical Working Party," 3 January 1962, Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.774, 8,15.

[115] Ibid., 15.

Advanced Power Systems unit ostensibly drew its funding exclusively from within Pratt & Whitney.[116] But the ECL reported that the division was responsible for a mix of commercial and military projects including alkaline electrolyte systems for the Army and Air Force.[117] Given that the term "commercial" in this context was virtually a euphemism for acidic fuel cells, it is likely that work on acidic and basic electrolyte systems in the Advanced Power Systems unit occurred almost literally side by side.

Moreover, the ECL report suggested that work in Pratt & Whitney's basic electrochemistry department, the Physical Chemistry Laboratory, was not rigidly divided along commercial and non-commercial lines. While this laboratory seemed to function largely in support of the Apollo project, providing basic research of immediate value to the engineering of aerospace cells, the ECL report noted that another program within this department was devoted to the development of electrodes, of which at least some had been tested with hydrocarbons.[118] This suggests a commercial motive, since hydrocarbons were never considered for aerospace fuel cell applications.

Finally, Podolny's claims in 1973 that Pratt & Whitney's commercial fuel cell program had no links to the government aerospace fuel cell program are at odds with the statements of company researchers and officials made in the late 1960s. In March 1968, Pratt & Whitney engineers informed ECL officials that their work with alkaline systems had provided them with valuable experience in developing the company's acid fuel cell technology.[119] Given that almost all of Pratt & Whitney's work in alkaline technology had been funded by NASA, this was virtually an admission that the federal government had played an indirect role in the development of the company's commercial fuel cell technology. Pratt & Whitney president B.A. Schmickrath was even more explicit, stating in April 1968 that knowledge obtained over the course of the space program was "invaluable" in enabling the firm to develop fuel cell designs with commercial potential. Seven years of "concentrated effort" for NASA had encouraged Pratt & Whitney to explore technological avenues that it had not considered a decade earlier, promising a "significantly different line of business in the future."[120]

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[116] A.D.S. Tantram, "Visit to Leesona-Moos and Pratt & Whitney," March 16-20 1964, Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.746, 2.3.
[117] Ibid., 4.1-4.3.
[118] Ibid., 4.6.

The available evidence suggests that NASA played a crucial indirect role in enabling Pratt & Whitney to develop its phosphoric acid fuel cell. But the space agency did not "drive" the company down a technological path it might otherwise have eschewed. Rather, the sole market in the early 1960s for what was then Pratt & Whitney's leading fuel cell technology, the alkaline Bacon cell, was the space agency. Naturally, the company became dependent on this aerospace market in the first half of the 1960s. With the federal government unwilling to subsidize a commercial fuel cell when this market diminished, Pratt & Whitney chose not to abandon the electrochemical infrastructure and expertise it had accumulated during the space program but instead decided to collaborate with the gas utilities. As Podolny admitted to ECL officials, the TARGET alliance was the only way the company could support its acid fuel cell research and development program in its new straightened circumstances.[121]

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[119] A.D.S. Tantram, "Visit Report 149: Pratt & Whitney: 25-28 March 1968 (Molten Carbonate cell discussions), Sylvania: 29 March 1968 (Iron Electrodes)," Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.762, 8.

[120] Space Division of North American Rockwell Corporation, "Space Program Benefits," 17 April 1968, Record Number 012978: Inventions From Space Program, 37-38, NASA Headquarters Archive.

Pratt & Whitney emerged from the Space Race as the premier player in fuel cell technology development. By the late 1960s, most of the other companies with major investments were shutting down their programs. Union Carbide pulled out at the beginning of 1969.[122] General Electric, for long one of the staunchest proponents of terrestrial fuel cells and the concept of aerospace "spin-offs," largely discontinued its work on the technology at the end of 1968. For several years afterwards, the company supported low-priority work at its Lynn facility to improve ion-exchange membranes in the vain hope that applications would be found in specialized aerospace and terrestrial commercial and military roles.[123]

In contrast, Pratt & Whitney/United Technologies Corporation produced aerospace fuel cells for NASA from 1966 until the late 1990s. In that period, it built 90 fuel cells for Apollo spacecraft and a further 25 for the Space Shuttle.[124] As we have seen, the Apollo contracts played an important role in helping the company comprehend the physical principles of the phosphoric acid fuel cell. Pratt & Whitney/UTC's collaboration with the gas utilities in TARGET between 1967 and 1976 further enlarged the firm's knowledge base and provided manufacturing experience. With the emergence of the energy crisis in the 1970s, the federal government became increasingly interested in the commercial potential of UTC's fuel cells. While NASA represented a small though consistent source of income during the 1970s, UTC's main government fuel cell patron after 1977 was the Department of Energy, the new federal energy administration.

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[121] Bacon's old collaborator T.M. Fry, then consulting for the ECL, reported that during a visit to the consortium's laboratories in 1970, Podolny informed British researchers that Pratt & Whitney's only hope for commercializing fuel cell technology lay, as Fry put it, in the "exploitation of the peculiar plight" of the gas industry. This, said Podolny, was a high-risk gamble in which the chances of success were slim. In the meantime, Pratt & Whitney hoped to assemble funds for exploratory development by, as Fry paraphrased, playing upon the "human characteristics of the presidents of gas-utility corporations;" T.M. Fry, "Visit of Mr. W.H. Podolny," 21 August 1970, Bacon TS, Section B, Research and Development, Background Material, B.1350, 2. Three years later, Podolny admitted to ECL officers that Pratt & Whitney had not conducted a rigorous appraisal of the commercial fuel cell field and had entered into the venture "as an act of faith;" C.G. James, "Visit to Pratt & Whitney, South Windsor Engineering Facility, East Hartford, Connecticut," 8 November 1973, Bacon TS, Section B, Research and Development, Background Material, 'Miscellaneous,' B.1352, 1.

[122] C.G. Clow, "Visit Report No. 183, USA, 14-22 May 1969, Part I: A Brief Status Report," Bacon TS Section B, Research and Development, Energy Conversion Limited, Reports, B.768, 1.

[123] Ibid., 8.

[124] King and O'Day, "Applying Fuel Cell Experience To Sustainable Power Products," 17.

Ironically, then, it was NASA, and not the Army or the Department of Defense, that played the key role in the genesis of commercial terrestrial phosphoric acid fuel cell technology. While Podolny complained that Pratt & Whitney's profit was only four per cent of the $100 million the federal government had spent on the Apollo fuel cell program, this was sufficient to pay the Leesona Corporation, which performed all of the company's basic research on acid hydrocarbon fuel cells in the 1960s.[125] The predictions made by NASA officials in the early 1960s had, in a sense, come to pass, for the space agency helped create the basis of a fledgling fuel cell industry. Backed by the financial support of the Department of Energy and with NASA supplying engineering research and systems analysis, UTC developed a series of multi-kilowatt natural gas-fuelled phosphoric acid demonstration utility fuel cells in the 1970s and 1980s. By the early 1990s, the company was ready to bring a mature design, the 200-kilowatt PC-25, to market, one it was well placed to monopolize thanks to almost thirty years of federal government support.

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[125] T.M. Fry, "Visit of Mr. Podolny," 21 August 1970, Bacon TS, Section B, Research and Development, Background Material, 'Miscellaneous,' B.1350, 1. Fry also stated that he had learned that the system of U.S. government contract work had resulted in the transfer to United Aircraft of supplementary disbursements worth several million dollars for engineering support in addition to payment for the original contracts.

Through its sponsorship of General Electric, NASA also played an indirect role in the development of the ion-exchange membrane fuel cell, a technology that would become the basis of efforts to commercialize fuel cells in the 1990s. By late 1983 and early 1984, with prospects of major new government orders for aerospace fuels dim and having failed to develop a viable commercial model despite almost thirty years of effort, General Electric sold its fuel cell business to UTC.[126] In the mid-1980s, at almost the same moment the world's leading manufacturer of electrical and power source equipment abandoned the membrane fuel cell, the concept was taken up by start-up companies like Ballard Power Systems, ending UTC's dominance in fuel cell research and development. In the 1990s, the promoters of improved membrane fuel cell technology would market it as a power source for the electric automobile, completely overshadowing utility applications and fostering new alliances among industry, media and government. It was in this application that fuel cell technology was for the first time propelled into the popular consciousness as a commercial abundant clean energy machine.

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[126] William Simon, interview by John Mauer, "Oral History with Bill Simon about Early Space Shuttle Development," 22 March 1984, Record Number 15557, Program: Shuttle, Location: SHU-INT2, 6, University of Houston-Clear Lake, Neumann Library; A.J. Appleby and E.B. Yeager, *Energy International Journal* 11 (1986): 137.

5 - Fueling Visions of Grandeur: The Fuel Cell as an Automotive Panacea

In September 2004, a group of scientists and engineers met at a conference at the Chemical Heritage Foundation (CHF) of Philadelphia. Part museum and part think-tank, the CHF is dedicated to celebrating the history of chemistry and charting the future course of the chemical industry. Gathering in the foundation's opulent headquarters in a renovated nineteenth-century bank, researchers discussed how to produce the materials needed to develop new products for the twenty-first century in the fields of optics, biotechnology, health and energy. Among the featured speakers was Charles Stone, head of research and development at Ballard Power Systems, a fuel cell development company that had been at the centre of the so-called green energy revolution of the 1990s. "I like to call them [Ballard fuel cells] products," Stone began, "but in reality they're advanced prototypes and demonstration units."[1]

This statement well conveyed the essential problem with efforts to bring this power source to market: the disjunction between performance under controlled laboratory conditions and sustained economic performance in the field. Over a period of two decades beginning in the mid-1980s, Ballard played a leading role in developing automobile fuel cells, popularizing that application to an unprecedented degree. While the fuel cell-powered electric vehicle had long been the dream of pioneer researchers like F.T. Bacon and Karl Kordesch, as well as the U.S. Army, commercial fuel cell development in the 1970s and 1980s focused largely on the stationary generator (utility) application, a field dominated by the Pratt & Whitney division of the United Technologies Corporation. This chapter will explore the reasons fuel cell research and development communities shifted emphasis away from utility applications and towards automobiles, a move that by the mid-1990s constituted the second postwar fuel cell boom.

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[1] Charles Stone, "Future Energy Sources," presentation at the First Annual Society of Chemical Industry-Chemical Heritage Foundation Innovation Day, Philadelphia, PA, 14 September, 2004.

As the sociologist Bruce Podobnik has noted, sophisticated new energy technologies, particularly oil, natural gas and nuclear systems, have historically been developed in periods of energy plenitude, not penury, and were developed for reasons other than energy demand.[2] The latter also holds true for the boom in automotive fuel cell technology. This represented a drastic change in North American automobile culture, for it seemed to signal the resurgence of the electric passenger car, a technology the petroleum and automobile industries had long opposed, at a time of near-record low oil prices.

Analysts typically attribute this development to two factors: rapid improvements in the membrane fuel cell, a technology well-suited to the requirements of the electric automobile, and a changing socio-political climate, in which Americans were increasingly sensitive to environmental and energy issues and receptive to technological solutions to these problems.[3] While these factors are important, they must be considered in light of the relationship between the material practices and economic needs of fuel cell research and development communities and the larger techno-scientific and industrial context within which these communities sought patronage and a market for their products. After the Second World War, the main problem facing these communities was how to fund their activities in the absence of a commercial product. As we have seen, while the federal government provided most of the resources for terrestrial and aerospace fuel cell research and development in the U.S., such support was intermittent. The primitive state of the art, the limited availability of electrochemical expertise and irregular cycles of government funding made commercial fuel cell research and development after the Second World War a highly speculative and tenuous enterprise.

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[2] Bruce Podobnik, *Global Energy Studies: Fostering Sustainability in a Turbulent Age* (Philadelphia: Temple University Press, 2006), 103.

[3] See Karl V. Kordesch and Günter Simader, *Fuel Cells and their Applications* (New York: VCH Publishers, 1996), 2; Charles Stone and Anne E. Morrison, "From Curiosity to 'power to change the world,'®" *Solid State Ionics*, 152-153 (2002): 2; Joseph J. Romm, *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate* (Washington, D.C.: Island Press, 2004), 12.

Under pressure to produce quick results and fearing the loss of support from a patron before a crucial "breakthrough" was made, fuel cell researchers often resorted to promises of future technological progress. This had an important effect on the conduct and reporting of research. Tests were typically configured to produce the highest possible current densities on notional laboratory devices. Often the results were trumpeted in the media before full-size fuel cells were subjected to thorough and long-term testing under realistic conditions.

As this chapter will demonstrate, conditions were ripe for a rapid expansion of fuel cell research and development in the United States by the late 1980s and early 1990s. As political pressure intensified for energy and transportation technologies that could respond to environmental concerns, and with venture capital easily available in the technology bubble of the 1990s, the automotive fuel cell appealed to a variety of interest groups as an uncompromising "abundant energy machine" capable of reconciling society's taste for the convenience of personal automotive transport with popular demand for environmental sustainability. As in the 1950s and 1960s, a diverse coalition of researchers, entrepreneurs and politicians with varying interests elevated fuel cell technology from obscurity. For Ballard, the automotive fuel cell represented nothing less than an opportunity to remake the existing transportation system and dominate the market for electrochemical automotive power sources. For the automobile and oil industries, fuel cells were an attractive alternative to conventional batteries as a power source for electric vehicles after California legislated the production of zero emission vehicles in 1990. And for state and federal governments, fuel cell power promised a way to end air pollution and wean America from its appetite for foreign oil.

For a brief time, the collective efforts of industry and government made the fuel cell the lodestone of American energy research and development policy and the centerpiece of the utopian energy and transportation order known as the hydrogen economy. Yet the architects of the latest fuel cell boom invested the technology with qualities wholly out of proportion to its actual capabilities. Attempts to market the fuel cell as an "abundant energy machine," a deep-rooted American dream,[4] ultimately ran afoul of the technology's physical limitations and the reluctance of industry and the federal government to make major investments in a fuel cell-based power and transportation system. As in the late 1960s, the resulting crisis of expectations in the early 2000s forced a reassessment of the role of fuel cell power.

From Utility to Automotive Power: Trends in Fuel Cell Ideology and Research and Development, 1970-1989

Fuel cell experts did not anticipate the rapid growth in research on automotive fuel cell systems in the 1990s. In the late 1980s, A.J. Appleby and F.R. Foulkes expected that the first commercial fuel cell application would "almost undoubtedly" be large and expensive multi-megawatt central electricity generating stations, since only they could capture the large markets and exploit the economies of scale that would justify major investments.[5] Writing in 1996, Karl Kordesch and Günter Simader agreed that fuel cell generators were likely to be first to market. The widespread application of automotive fuel cells, they reasoned, was less likely for a number of reasons. Most importantly, none of the existing technologies met all the economic and technical criteria.[6] Kordesch, Appleby and Foulkes favored alkaline fuel cells for vehicular applications for all the traditional reasons: these designs did not require platinum and had much better start-up performance than the phosphoric acid design. In the late 1980s and early 1990s, the latest ion-exchange membrane fuel cells started rapidly and offered high power, but the membrane was still prone to dehydration and cracking under certain operating conditions. Further, such fuel cells required expensive materials, not only platinum, like all acid designs, but also the polymer membrane, which then cost about $400 per square meter. There was also the perennial question of fuel supply. An alkaline fuel cell electric vehicle required cheap hydrogen and the cost of producing and distributing this fuel had been a prime reason American industry and the federal government had begun research on acid fuel cell technology in the 1960s. Appleby and Foulkes predicted the first commercial fuel cell automobiles would not be light duty passenger vehicles, which required an extensive hydrogen infrastructure, but rather "subsidized fleet vehicles" like buses, which could be readily fuelled and serviced from a central depot.[7]

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[4] John Byrne and Daniel Rich, "In Search of the Abundant Energy Machine," in *Energy Policy Studies: The Politics of Energy Research and Development*, vol. 3, eds. John Byrne and Daniel Rich (New Brunswick, NJ: Transaction Books, 1986), 141.

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[5] A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), 14.
[6] Kordesch and Simader, *Fuel Cells and their Applications*, 6-7;

In order to understand the shift in conceptions of the fuel cell as a specialized power source for stationary applications with *important* environmental and economic benefits in the 1970s and 1980s to a universal energy converter for electric automobiles with *revolutionary* socio-economic and ecological potential in the 1990s, we must examine the development of commercial fuel cell research and development and its connections with the idea of the hydrogen economy. In Chapter Four, we saw how the Pratt & Whitney division of the United Aircraft/United Technologies Corporation emerged from the space race as the dominant player in this nascent field. Beginning in the late 1960s, this company, the gas utilities, NASA and, after 1977, the Department of Energy, kept alive the idea of large-scale electrochemical power generation through their efforts to commercialize fuel cell technology. In turn, this helped encourage analysts and researchers to develop their own alternative fuel cell power schemes, ideas that would find their greatest opportunity for expression at the height of the automotive fuel cell boom in the early 2000s.

Although the TARGET partners had relatively limited expectations of fuel cell technology, the program inspired a diverse group of technologists including electrochemists and gas and electrical specialists with a vision of a utopian energy order that promised to reconcile consumerism with the rise in environmental consciousness, influencing the way people thought about fuel cells and the ways they might impinge on their daily lives. This was the so-called "hydrogen economy," a vast, decentralized energy production and distribution system its architects claimed would reconcile supply with environmental sustainability in one bold stroke. This futurist scheme gained brief currency in the early 1970s before falling into obscurity over the next twenty years. At the turn of the millennium, the concept was revived, this time in association with the fuel cell automobile. The idea of a society powered by limitless clean hydrogen would become a crucial subtext in the mass marketing of the fuel cell automobile as a panacea for the ills of the old energy order.

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[7] Appleby and Foulkes, 187-189, 201. Appleby calculated that there was sufficient platinum to produce only 800,000 20-kilowatt vehicle powerplants per year, less than three percent of world automobile production in 1986.

As with so many technologies and technological systems, the precise origins of the idea of a fuel cell-based hydrogen economy are unclear. What is known is that between 1970 and 1972, a loosely-associated group of electrochemists including John O'M. Bockris, Derek Gregory and A.J. Appleby sketched drafts of a plan in which hydrogen served as the basis for an all-encompassing energy system.[8] This emulated TARGET, except that hydrogen replaced natural gas as the fuel and energy carrier. What was more, fuel cells in a hydrogen economy would serve as the energy converter not only in stationary but vehicular applications as well. Heavily influenced by the Italian physicist Cesare Marchetti, the hydrogen futurists envisioned a distant time when fossil fuel supplies were virtually exhausted and the only remaining primary energy source was nuclear power.[9]

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[8] Of these individuals, Bockris was most interested in tracking the intellectual provenance of the "hydrogen economy." In late 1973, Bockris wrote Bacon, suggesting that the origins of the concept lay in Bacon's idea of 1952-53 to use wind turbines to electrolyze water, which would then be run through a fuel cell. Bacon declined credit, claiming that the "hydrogen economy" was Gregory's idea. Bacon added he had first encountered the notion of a solar-hydrogen economy in Eduard Justi's *Leitungsmechanismus und Energieumwandlung in Festkörfern* (Gottingen, 1965). Bockris eventually claimed that, inspired by a meeting with Bacon and Watson in 1952 or 1953, it had been he, Bockris, who had most fully articulated the idea of a hydrogen economy; John O'M. Bockris to Francis Thomas Bacon, 12 November 1973; Bacon to Bockris, 10 December 1973, Bacon TS, Section G, Correspondence, Fuel Cell Correspondence G.148; Bockris to Bacon, 15 January 1974, Bockris to Bacon, 9 February 1974, Bacon TS, G.149.

The most detailed version of the plan was developed for the American Gas Association, the professional organization of the gas utilities, by the Institute of Gas Technology (now the Gas Technology Institute), a non-profit research center. Written by Gregory with input from the chemical and electrical industries and NASA, the plan combined the "approaches of both TARGET and the space program."[10] Assuming that energy demand would continue to grow in the future, the scheme envisioned giant nuclear plants, including some moored on huge concrete islands, each generating between 5000-10,000 megawatts.[11] Nuclear-powered reversible fuel cells would electrolyze water during periods of low demand, storing the hydrogen in vast underground caverns until needed. Because these plants would be isolated, the reasoning went, it would be uneconomic to transmit the electricity they produced through high-tension power lines. Instead, electricity would be stored and efficiently transported over vast distances by converting it into hydrogen, which would be piped or shipped as a compressed gas or a cryogenic liquid. The hydrogen would then be converted into electricity by fuel cells at the point of use.[12]

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[9] D.P. Gregory, D.Y.C. Ng and G.M. Long, "The Hydrogen Economy," in *Electrochemistry of Cleaner Environments*, ed. John O'M. Bockris (New York: Plenum Press, 1972), 229; John O'M Bockris and A.J. Appleby, "The Hydrogen Economy-An Ultimate Economy? A Practical Answer to the Problem of Energy Supply and Pollution," *Environment This Month* 1, no. 1 (July 1972): 30.

[10] D.P. Gregory, et al., *A Hydrogen Energy System* (American Gas Association, 1973), 1, VII-29.

[11] Marchetti's schemes were the most radical of all the hydrogen utopians. His so-called "energy island" consisted of five one million-ton concrete barges, each of which would carry one 200-gigawatt nuclear reactor. Each "island" would have a combined power of one terawatt or one trillion watts, the equivalent of 1000 conventionally-sized 1000-megawatt power plants. Nine of these islands, moored in strategic locations around the world, would produce uranium from seawater and electrolyze water into hydrogen, which would then be liquefied and transferred to special tankers. Nuclear waste would be dropped through shafts punched into the ocean floor, where it would melt its way deeper into the basalt crust, presumably becoming entombed for eternity; Peter Hoffmann, *The Forever Fuel: The Story of Hydrogen* (Boulder, CO: Westview Press, 1981), 234-235.

While the ideas of the hydrogen futurists generally remained on the fringes of energy policy circles in the early 1970s, NASA began to promote a version of the hydrogen economy as it sought a role in the Nixon administration's reorganized federal energy research and development establishment. In response to the Atomic Energy Commission's survey of resources that federal agencies might contribute to Nixon's proposed $10 billion five-year energy research and development program, NASA submitted a proposal citing 43 program areas it felt competent to manage. One of these encompassed hydrogen fuel and hydrogen fuel cells, technologies it had pioneered in the space program.[13] James C. Fletcher, NASA's administrator, followed up this submission with a personal appeal to the director of the Office of Management and Budget. First among Fletcher's appended proposals was one for an energy system based on hydrogen. He understood this as a "universal" fuel attractive for its pollution-free combustion that could be produced from coal and water electrolysis and distributed via a national network of pipelines.[14]

Reviews of the plan were skeptical. The National Academy of Engineering held that NASA lacked experience and accomplishments in fields requiring an understanding of the civilian marketplace and had devoted little thought to precisely how aerospace technologies would be transferred for commercial use. The NAE was also surprised that NASA's planning was so heavily weighted on sweeping long-term visions like the hydrogen economy, given that its structure as a mission agency made it better adapted to high-priority, short-term programs. What was more, the NASA proposal contained no details on cost, timelines and the role of industry.[15] Some fuel cell hands within the space agency were similarly unimpressed. In a series of letters exchanged with Bacon in 1973 and 1974, Ernst Cohn dismissed the hydrogen economy as "not a very good idea." While hydrogen remained the only practical fuel cell fuel at that time, Cohn believed it was slowly losing its appeal among pundits amidst a new reappraisal of methanol, a material he saw as much more economically and technologically promising.[16]

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[12] D.P. Gregory, et al., *A Hydrogen Energy System*, 5-13.

[13] George M. Low, Deputy Administrator, to Robert C. Seamans, Jr., President, National Academy of Engineering, 2 October 1973, Record Number 013547, Special Collections, NASA Administrators, Congressional Documents, George M. Low Papers, Energy-Part 2, NASA Headquarters Archive.

[14] James C. Fletcher to Roy L. Ash, 11 October 1973, Record Number 009819: Energy, NASA Documentation, NASA Headquarters Archive.

Like NASA officials, the hydrogen futurists never specified exactly how society would wean itself from fossil fuels as it moved to fuel cells and the hydrogen economy. Gregory wrote that he and his team had developed their analysis not as a "clear-cut case" detailing how a transition to the hydrogen economy might occur, but rather as a way to raise questions about technological options and stimulate long-term planning.[17] In 1973, the American Association for the Advancement of Science endorsed the ideas of the hydrogen futurists.[18] By accepting the premise of a hypothetical fully-formed hydrogen economy, the AAAS, like the futurists, avoided addressing precisely how fuel cells and hydrogen production, storage and distribution technologies would be introduced into society, let alone their socio-economic and political consequences. In short, the "hydrogen economy" was an ideologically conservative critique of the status quo that equated technological progress with social progress and refrained from outlining a blueprint for change. In these senses, it resembled the classic American technological utopias, a literary genre that flourished between the 1880s and 1930s, of which Edward Bellamy's 1888 novel *Looking Backward* was the exemplar.[19]

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[15] Ad Hoc Panel of National Academy of Engineering, "Informal Review of NASA Energy Research and Development Proposals," 19 November 1973, Record Number 013547, Special Collections, NASA Administrators, Congressional Documents, George M. Low Papers, Energy-Part 2, p.2, NASA Headquarters Archive.

[16] Cohn to Bacon, 8 February 1974, Bacon TS, Section G, Correspondence, Fuel Cell Correspondence, G.149.

[17] D.P. Gregory, D.Y.C. Ng and G.M. Long, "The Hydrogen Economy," in *Electrochemistry of Cleaner Environments*, ed. John O'M. Bockris (New York: Plenum Press, 1972), 229.

[18] Allen L. Hammond, William D. Metz and Thomas H. Maugh II, *Energy and the Future* (Washington, D.C.: AAAS, 1973), 99, 109, 117.

Hydrogen fuel cells and hydrogen futurism were never serious elements in federal energy policy in the 1970s and faded almost completely from view as planners focused on price controls and, in the Carter administration, on coal, synthetic fuels and solar power. Fuel cells had a low profile until the end of the decade, when the federal government reprised its research and development relationship with Pratt & Whitney/United Technologies Corporation. This time, the emphasis was on hydrocarbon utility generators. In 1977, the Department of Energy, NASA and the private sector Gas Research Institute joined to support UTC's latest utility fuel cell project, the 40-kilowatt PC-18, a phosphoric acid model under development since 1974 and derived from the PC-11 developed for TARGET.[20] Federal assistance made this the largest fuel cell program of the 1980s, one that ultimately led to the PC-25, the first commercial fuel cell.

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[19] Howard P. Segal, *Technological Utopianism in American Culture* (Chicago: University of Chicago Press, 1985), 1-22.

[20] U.S. Department of Energy, *Onsite 40-Kilowatt Fuel Cell Power Plant Manufacturing and Field Test Program, DOE/NASA/0255-1, NASA CR-174988* (Washington, D.C: 1985), 1-1, 1-2, 2-4. Unlike the PC-11, but in common with multi-megawatt central stations demonstrators developed by UTC in the 1970s and 1980s, the PC-18 was designed to recover and use the waste heat produced during its operation for water and space heating, a configuration known as co-generation. This allowed the manufacturer to boost the unit's rated efficiency from 40 per cent when generating only electricity to 80 per cent when the recycling of waste heat was taken into account. This meant that potential customers for such systems had to factor in the costs of retrofitting industrial or residential buildings to accommodate thermal heating systems if they wanted to take full advantage of the fuel cell generator's efficiency

In 1981, the two federal agencies and the Gas Research Institute supported UTC in a pilot manufacturing project. The $34 million, 42-month effort was designed to evaluate the "on-site" fuel cell concept and perfect techniques of serial production, distribution and field support in preparation for introduction into general commercial service in the gas industry.[21] NASA's role was limited to prospective testing and analysis of the design in preparation for field trials.[22] Between 1984 and 1986, 53 PC-18s were manufactured and field-tested by gas utilities and the U.S. military. They were very expensive, averaging $12,500 per kilowatt or $500,000 per unit, and had a lifetime of around 7000 hours or around 290 days of 24-hour operation.[23] Believing the 40-kilowatt model too small to be commercially viable, UTC began work on a 200-kilowatt version known as the PC-25, a project that received further funding and diagnostic and testing support from the Department of Energy and NASA.[24]

In the mid-1980s, after almost twenty years of effort, UTC was on the verge of commercializing stationary phosphoric acid fuel cells. When the company's 11-megawatt PC-23 failed to attract interest, the company opted to produce the PC-25, entering into a joint venture with the Japanese engineering firm Toshiba in 1985.[25] Such private sector collaboration was a likely factor in the decision of Congress to end subsidies for this program in 1987, despite protests from the Department of Energy. Over a period of ten years, the federal government provided $334.7 million in direct assistance for phosphoric acid utility fuel cells in addition to NASA's indirect support dating back to the mid-1960s.[26] Three bills introduced in Congress in May 1987 by California Representative George E. Brown proposing research on renewable hydrogen and a national policy on hydrogen fuel cell development were referred to the subcommittee on energy research and development and never left the House.[27] By 1988, there were over 30 orders for the PC-25.

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[21] Ibid., 1-1.

[22] Ibid., 2-14, 2-15. NASA tried to exploit its involvement in this project as evidence of the economic benefits of the space program. Its official press release focused on the use of phosphoric acid fuel cells in hospitals and commercial and residential establishments, claiming that these were "larger terrestrial versions of the systems used to generate electricity in the nation's manned space program;" NASA News Release No. 82-127, "NASA Awards Fuel Cell Technology Development Contract," 23 August 1982, Record Number 013761: Propulsion, Auxiliary Power Fuel Cells, Memos, News Releases, NASA Headquarters Archive, 2.

[23] A.J. Appleby, *Energy* 12 (1986): 13.

[24] Marvin Warshay, NASA, *Status of Commercial Fuel Cell Powerplant System Development,* prepared for the U.S. Department of Energy for the 22nd Intersociety Energy Conversion Engineering Conference, Philadelphia, Pennsylvania, August 10-14, 1987, DOE/NASA/17088-5, NASA TM-89896, AIAA-87-9081, 3.

While UTC had periodically invoked environmental justifications for its utility fuel cells during the 1970s, it and its clients saw the phosphoric acid fuel cell simply as an efficient type of power generator, not a solution in and of itself for the problem of air pollution. Nowhere in the 162-page summary of the PC-18 program were environmental justifications advanced. Gas and electrical utilities were interested in fuel cell technology for its potential efficiency and flexibility. Because the efficiency of fuel cells remained the same regardless of the size of the power unit and because individual stacks could be clustered if necessary, fuel cell power plants could, in theory, be gradually enlarged to match the growth in electrical demand in a way that conventional steam or nuclear plants could not, reducing excess capacity.[28] Fuel cell systems of any kind, whether using hydrocarbons or hydrogen, excited little interest among environmentalists in this period. Major figures in alternative energy circles such as Amory B. Lovins made almost no mention of fuel cells in numerous papers and books written in the 1970s and 1980s.[29] Peter Hoffmann's 239-page popular history of hydrogen, published in 1981, devoted only a half-page to fuel cells.[30] As late as 1989, hydrogen advocates like Joan Ogden envisioned using hydrogen in internal combustion engines, not fuel cells.[31]

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[25] Appleby, "Issues in Fuel Cell Commercialization," *Journal of Power Sources* 69 (1996): 160.

[26] Warshay, 4, *Congressional Record*, 100th Cong., 1st sess., 1987, 133, Attachment C, 12, E 2135.

[27] http://thomas.loc.gov/cgibin/bdquery/?&Db=d100&querybd=@FEILD(FLD001+@4(Research+and+development), accessed 12 January, 2007.

[28] Marvin Warshay, *Status of Commercial Fuel Cell Powerplant System Development*, 2.

It was only in the 1990s that industrialists, researchers and venture capitalists began to tout the fuel cell as a solution to the energy and environmental crises. This occurred strictly in relation to its application in the electric automobile. Over the course of the decade, billions of dollars flowed into fuel cell automobile programs, dwarfing previous investments in fuel cell technology. As with all preceding efforts, however, fuel production and storage remained the biggest obstacles. As we shall see, government and industry's attempt to reconcile smooth operation in the fuel cell reactor itself with the economics of a fuel cell-based transportation system - the old debate between the benefits of hydrocarbon and hydrogen fuel - would lead to the revival of the idea of the hydrogen economy by the end of the decade. This provided the institutional framework within which fuel cell technopolitics could be played on a truly vast scale.

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[29] Lovins wrote practically nothing about fuel cells until well into the 1990s.

[30] Peter Hoffmann, *The Forever Fuel: The Story of Hydrogen*. Twenty years later, Hoffmann wrote another book that linked hydrogen with fuel cells as an environmentally-friendly energy system; see *Tomorrow's Energy: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet* (Cambridge, MA: The MIT Press, 2001).

[31] Joan M. Ogden and R.H. Williams, *Solar Hydrogen: Moving Beyond Fossil Fuels* (Washington; D.C.: World Resources Institute, 1989).

The Fuel Cell and the Electric Automobile

The history of the fuel cell is interwoven with the history of the conventional galvanic battery, and the application of both of these electrochemical power sources in the electric automobile is no exception. In important ways, the history of the fuel cell automobile is but the latest unwritten chapter of the history of the battery-powered electric car. Recent scholarly analyses of electric vehicles mention fuel cells as the most recent effort to develop an electrochemical power source sufficiently powerful and reliable to finally make electric drive competitive with gasoline vehicles. While work by historians like Gijs Mom and David A. Kirsch does not address fuel cell development, the socio-technical relationship between fuel cells and batteries, or applications of fuel cells in electric vehicles, it does provide an invaluable conceptual framework in understanding the history of electrochemical electric drive in relation to internal combustion power.[32] In turn, this affords valuable insight into the social phenomenon of fuel cell development in general and efforts to commercialize electric vehicles in the 1990s and early 2000s in particular.

Mom and Kirsch supply a corrective to the belief that the question of whether batteries or fuel cells would dominate would be ultimately decided by objective economic and technological factors, the "economics of the energy supply chain," the most efficient way of producing primary energy and transferring it for use in an automobile.[33] Drawing on the social constructivist approach to the history of technology, they question the whiggish tautologies of traditional accounts of automobile history, the view that the internal combustion vehicle "was the best because it won and won because it was the best."[34] In place of the idea that the gasoline vehicle was the optimum technology, Mom and Kirsch hold that notions of technological superiority are largely grounded in the subjective judgments of engineers, designers, marketers and industrialists in given socio-economic contexts. The idea of the inferiority of battery electric drive in relation to gasoline vehicles as a consequence of short range due to limited storage capacity has been derived from culturally rooted ideas of what is desirable in an automobile. These in turn have constantly changed with new developments in vehicular power sources and in the petroleum and electrical infrastructure, in which government has played a key role.

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[32] David A. Kirsch, *The Electric Vehicle and the Burden of History* (New Brunswick, NJ: Rutgers University Press, 2000); Gijs Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age* (Baltimore: The Johns Hopkins University Press, 2004).

[33] Appleby and Foulkes, *Fuel Cell Handbook*, 179.

Mom and Kirsch focus on several key points in explaining the demise of the battery electric vehicle. They emphasize that the socially determined nature of expectations coupled with fundamental differences in the operating systems of internal combustion and battery electric engines had important consequences in terms of the types of infrastructure necessary to support vehicles powered by these systems. A fundamental feature of the history of the technological development of gasoline and battery electric vehicles is design reciprocity. Developers of each respective class of automobile tried to embody the best features of the competing technology in their own designs. Both types of power sources had offsetting pros and cons. In certain circumstances, battery electric vehicles had historically performed well in comparison with their gasoline counterparts. Beginning in the late nineteenth century and into the second decade of the twentieth century, battery-powered electric vehicles replaced horse-drawn carriages and elite luxury coaches. The cost and performance of these vehicles, above all, range, was judged favourably in relation to the older mode of transport as well as to new gasoline vehicles, then regarded as smelly, noisy and unreliable. As battery technology was improved in the second decade of the twentieth century, some European cities found electric taxicabs and municipal vehicles both aesthetically preferable and economically competitive if operated in large fleets served by centralized charging and maintenance facilities.[35]

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[34] Kirsch, *The Electric Vehicle and the Burden of History*, 17.

While early gasoline vehicles were much less reliable and comfortable than urban electric cars, and less suited for operation in cities, their greater range and speed was exploited in the U.S. by automakers who promoted the gasoline car as an adventure vehicle. This led to the emergence of "touring," long-distance jaunts though the American countryside, as a new cultural pursuit. Automakers improved the reliability, comfort and styling of gasoline vehicles, making them "multifunctional," able to compete with electrical vehicles in cities while retaining the long range that facilitated touring. With new aesthetic and performance standards thus defined, proponents of electric automobiles sought to develop a "universal" electric car with its own adventure cachet. They adopted the styling of the latest touring gasoline sedans and worked to develop a "miracle battery" that would even the playing field. Yet the resulting vehicles could still not match the gasoline automobile in range.[36]

Mom challenges Richard H. Schallenberg's view that the universal electric passenger sedan failed because of inherent performance shortcomings of lead-acid battery technology.[37] That such vehicles did not become ubiquitous, claims Mom, stemmed from the respective technological and cultural implications of gasoline and electrical vehicles and the historical development of the infrastructure necessary to support such vehicles. Mom notes that the first gasoline and battery electric vehicles produced around the turn of the century had maintenance and infrastructure requirements that led to a cultural predilection for the former. The operating principles of gasoline engines were so widely known that motorists commonly acted as their own mechanics. In comparison, batteries were inscrutable black boxes that could be properly serviced only by technicians who had received some formal electrochemical training.[38]

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[35] Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age*, 170.

[36] Ibid., 256-257.

[37] Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (Philadelphia: American Philosophical Society, 1982), 252-256.

Where infrastructure was concerned, Mom holds that builders of large centralized electrical power grids like Samuel Insull used battery electric vehicles as a tool in their battle against decentralized smaller stations. They saw vehicle batteries as a means of storing excess electricity and improving load factors. To this end, central station owners favored electric delivery trucks over cars because they had larger batteries and used more power. They built a network of centralized recharging garages, producing a fleet of electric vehicles optimized for industrial use in large cities. However, the uneven development of the American electrical grid inhibited the further spread of electrical vehicles of all kinds. In contrast, motorists could obtain cheap tins of fuel and spare parts at general stores throughout rural America. Consequently, the success of the gasoline system in its early days, holds Mom, owed something to its initial decentralized state.[39]

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[38] Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age*, 124-128.
[39] Ibid., 207-210.

Geopolitical and military considerations led the governments of industrialized nations to shift to oil-based energy and transportation systems prior to and during the First World War. Britain's Royal Navy began to replace coal with oil in the first decade of the twentieth century, a move emulated by other navies and in military land vehicles as well.[40] Although the U.S. Army favored electric drive in trials in the late 1890s, the federal government supported the development of petroleum infrastructure and transport. American industry produced tens of thousands of gasoline vehicles for the Allied armies, mainly trucks, many of which replaced electric trucks as war surplus, ending the era of general electric road transport. Non-rail electric vehicles were relegated to off-road industrial roles hauling materials in conditions were they were considered to have safety advantages over gasoline vehicles, particularly in enclosed factory spaces.[41]

The demise of electric vehicles was thus culturally determined. Mom argues that the short range of lead-acid batteries was not an absolute failing. Had the electrical utilities and the federal government deemed it desirable, a widespread system of recharging points could have been built that would have enabled battery electric passenger automobiles to compete with gasoline cars as an "adventure vehicle," negating the issue of range. Instead, the relevant actors had techno-political priorities that in the long run led them to adopt gasoline transport. The question of why this became the dominant system, Mom argues, was less a narrowly technical issue than a socio-political one.[42]

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[40] Bruce Podobnik, *Global Energy Shifts: Fostering Sustainability in a Turbulent Age* (Philadelphia: Temple University Press, 2006), 64-69.
[41] Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age*, 238-243.
[42] Ibid., 285.

Kirsch suggests that the discourse of automotive technology has reduced the issue to one of narrow performance comparisons between power sources in circumstances where the automotive industry was constantly improving gasoline vehicles, creating new benchmarks that battery technologists had little chance of matching, let alone surpassing. Yet battery technologists never really abandoned hope that a "miracle" battery would one day narrow the gap and make electric vehicles competitive. When air pollution and the energy crisis produced the political space for a reassessment of electric passenger vehicles beginning in the 1960s, the resulting government research programs focused on improving battery performance, neglecting infrastructure and demonstration projects.[43]

Mom and Kirsch note that the upsurge in fuel cell research in the 1990s was the latest episode in the quest for the miracle automotive battery in the sense that technologists reductively focused on the power source itself. They defined success in terms of a "breakthrough" in battery performance that would match the gasoline vehicles in every way. This meant that technologists tended to perceive even the latest battery systems as obsolete almost as soon as they were developed. For them, the ideal battery was always in the future.[44]

The Long Gestation of the Fuel Cell Electric Automobile

Despite similarities in the developmental arcs of fuel cell and battery electric vehicles, the automotive fuel cell projects of the 1990s were not simply another effort to build a miracle battery giving the electric passenger car the same range as its gasoline counterpart. The major automakers had long been hostile to battery electric drive, yet they enthusiastically embraced the fuel cell, touting it as a *non-battery* solution to electric drive that could be introduced into the existing hydrocarbon fuel infrastructure with few modifications. The dream of developing a miniature hydrocarbon fuel cell, abandoned in the 1960s, was revived, with the zero emission quality of the technology now figuring as a major selling point.

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[43] Kirsch, *The Electric Vehicle and the Burden of History*, 206.
[44] Mom, 273, Kirsch, 226.

Researchers had been intrigued with the possibility of using the power source in electric vehicles almost as soon as the first practical fuel cells began to appear in the late 1950s and early 1960s. The first serious studies of the comparative merits of battery versus fuel cell electric drive were undertaken in Britain and the United States in the 1960s. F.T. Bacon believed his fuel cell could be relatively easily introduced as a replacement for conventional batteries in Britain, which had a well-entrenched culture of short-range electric delivery vehicles dating back to the late 1940s.[45] In 1964, Bacon promoted the fuel cell "town car" as a solution to air pollution in the United Kingdom.[46]

In 1966, the British Ministry of Technology considered the fuel cell important enough to warrant the striking of a special working party made up of officials from the transport and electrical bureaucracies to consider the issue.[47] While the Ministry of Transport supported electric drive, it expressed no preference for the power source, suggesting that fuel cells in their current form held no obvious advantages over batteries in this role.[48] British electricity officials held a similar view.[49] The Electricity Council opted for conventional lead-acid batteries in the first major post-war electric city car experiment in Britain, the Enfield 8000, comprising 112 vehicles distributed to 12 electricity boards in England and Wales between 1966 and 1976.[50]

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[45] Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age*, 268-269; Michael H. Westbrook, *The Electric Car: Development and Future of Battery, Hybrid and Fuel-Cell Cars* (London: The Institution of Electric Engineers, 2001), 20. Westbrook states that some 20,000 electric delivery vehicles were built in Britain in the late 1940s and early 1950s, most of which remained in service into the 2000s.

[46] Unpublished notes, F.T. Bacon, "Note on Future Development Programme at ECL," 14 December 1964, Bacon TS, Section B, Research and Development, Energy Conversion Limited, 'Reports,' B.677.

[47] Internal Memo, Ministry of Technology, "Fuel Cell Working Party: Possible Uses of Fuel Cells and User-Requirements (Ref. Minute No. 4 of the 2nd Meeting of the Working Party on Fuel Cells,)" 11 January 1967, Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, 'Leesona-Moos and P&W,' B.1168. The memo's author made a point of noting that electric drive was already well established in Britain, citing numbers of electric vehicles considerably higher

Only a handful of fuel cell electric demonstration vehicles were built between the mid-1960s and late 1980s, mainly in the United States. Early tests seemed promising, but more sophisticated experiments revealed a variety of problems. In 1959, Allis-Chalmers demonstrated the first fuel cell vehicle, an electric tractor powered by a 15-kilowatt alkaline fuel cell.[51] The first experiment comparing fuel cells with batteries in electric drive vehicles was begun by General Motors in 1964. Its Electrovair-Electrovan demonstration program was premised on the then-widespread belief that

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than Westbrook's estimate: 40,000 commercial delivery vehicles and 60,000 materials and product handling vehicles.

[48] Ministry of Technology, "Minutes of the 4th Meeting of the Working Party on Fuel Cells Held at Ministry on Monday 23rd January 1967," Bacon TS, Section B, Research and Development, Research Centres, Laboratories and Sponsors, 'Leesona-Moos and P&W,' B.1169.

[49] A survey of automotive technologies conducted for Energy Conversion Limited in 1966 noted that while the advent of automotive emissions legislation provided an additional rationale for fuel cell electric drive, the weight of such systems, as well as lack of data on capital and operating costs, essentially ruled out their use in light duty vehicles. Those automotive applications of fuel cell-based electric drive that were likely to be economically and technologically feasible involved applications where weight and cost were not necessarily handicaps, narrowing the field of choice to specialized industrial vehicles such as aircraft air-conditioning starter units and large earthmovers. This mirrored the fate of battery electric vehicles after the 1920s. The report also cast doubt that fuel cell-powered vehicular electric drive would be an effective technological solution for air pollution; P.R. Hall and A.E. James, "Report No. 66/321A/RI: A Survey of Vehicles to Assess Their Suitability as Applications for the Fuel Cell," October 1966, Norris Brothers (Research & Development, Ltd.) for Energy Conversion, Ltd., Bacon TS, Section B, Research and Development, Energy Conversion Limited, Reports, B.777.

[50] Westbrook, *The Electric Car*, 20-21.

[51] This one of two events along with the demonstration of the Bacon cell that Gerrit Jan Schaeffer claims were chiefly responsible for spawning the fuel cell boom of the 1960s; Gerrit Jan Schaeffer, *Fuel Cells for the Future: A Contribution to Technology Forecasting From a Technology Dynamics Perspective* (Ph.D diss., University of Twente, 1998), 171.

fuel cells could be operated much longer than conventional batteries due to the fact that fuel was stored separately from the energy converter, the fuel cell stack itself. In theory, this represented a solution for the short range of battery electric vehicles. The resulting fuel cell vehicle, the Electrovan, obtained these perceived advantages at the cost of high weight and complexity. At 3220 kilograms, it was almost twice as heavy as a standard General Motors van and had a range of between 160-240 kilometers. The Electrovan could not be started with a "simple turn of a key;" as with Pratt & Whitney's aerospace PC-3A2, the vehicle's Union Carbide-built alkaline fuel cell was very sensitive and required more than three hours to start in order to avoid damaging or destroying it.[52]

In 1966, the Army's Mobility Command refitted a three-quarter ton truck with four five-kilowatt Monsanto hydrazine fuel cell stacks in order to test electric drive.[53] In the late 1960s, Union Carbide's chief battery and fuel cell expert Karl Kordesch converted an Austin A40 compact car to fuel cell power as a short-range "town car." He claimed that with regular maintenance, his battery/fuel cell hybrid power plant had a lifetime of about 2000 hours, comparable to the average internal combustion engine. However, this configuration was never adopted by any sponsor.[54] In 1968, a team at Shell's Thornton Research Centre in London installed a hydrazine fuel cell in a DAF 44 compact car to test control problems of fuel cell electric drive. Shell engineers compared the car favorably with other experimental battery and fuel cell electric passenger vehicles of the time, including the British Enfield and Kordesch's Austin. But they admitted there was little chance of commercializing such a vehicle owing to the high cost of hydrazine, concluding that there seemed few technological options that could make fuel cell vehicles viable.[55]

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[52] Craig Marks, Edward A. Rishavy and Floyd A. Wyczalek, "Electrovan-A Fuel Cell Powered Vehicle," *Automotive Engineering Congress and Exposition, Detroit, Michigan, January 9-13, 1967* (New York: Society of Automotive Engineers, 1967), 9, 13.

[53] James R. Huff and John C. Orth, "The USAMECOM-MERDC Fuel Cell Electric Power Generation Program," in *Fuel Cell Systems-II: 5th Biennial Fuel Cell Symposium Sponsored by the Division of Fuel Chemistry at the 154th Meeting of the American Chemical Society, Chicago, Illinois, September 12-14, 1967* (Washington, D.C: American Chemical Society, 1969), 323-326.

[54] Kordesch and Simader, *Fuel Cells and their Applications*, 257, 290. This was purely Kordesch's initiative, not an official Union Carbide project. Nevertheless, the vehicle did achieve some local notoriety on roads near the Union Carbide facility at Parma, Ohio in the early 1970s.

The energy and environmental crises of the late 1960s and 1970s finally provided the political and economic rationale for demonstrations of larger numbers of electric passenger vehicles in Europe and the United States. All used battery power.[56] The largest was the Electric and Hybrid Vehicle Research, Development and Demonstration Act (EHVRDDA), passed by Congress over President Gerald Ford's veto in 1976. Designed to "determine the commercial feasibility of electric vehicles," the law authorized a survey of consumer preferences, the drafting of performance standards and assessing infrastructure requirements and incentives to support the manufacture of 7500 electric vehicles.[57]

About 1100 vehicles were built before the program was cancelled by the Reagan administration.[58] The technopolitics of this battery research and development program set a pattern that would be repeated in the fuel cell electric drive programs of the 1990s. As Kirsch notes, the EHVRDDA focused on developing a super battery that would make electric drive competitive with the incumbent gasoline engine technology. This standard created a perpetual cycle where battery performance would always be considered inadequate, providing an excuse not to deploy the technology "prematurely" lest the public lose confidence in electric drive. The bulk of funds therefore went to basic research, not to infrastructure or demonstration programs.[59]

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[55] M.R. Andrew, W.J. Gressler, J.K. Johnson, R.T. Short and K.R. Williams, "A Fuel-Cell/Lead-Acid Battery Hybrid Car," in *Fuel Cell Technology for Vehicles*, ed. Richard Stobart (Warrendale, PA: Society of Automotive Engineers, 2001), 9, 11. Shell engineers ruled out the direct use of hydrocarbons as well as on-board fuel reformer technology as too difficult to control and taking too long to start up. They speculated that if a cheap catalyst could be found, methanol was the most attractive fuel.

[56] In the 1970s, electric passenger cars were commercially produced in small quantities by a number of start-up companies including Sebring-Vanguard in the U.S. and Electraction in the United Kingdom. Blue-chip industry contributed a few demonstration passenger electric cars including General Electric's Centennial Electric, Chevrolet's Electrovette and American Motors' Postal Van; Mom, *The Electric Vehicle*, 271, Westbrook, *The Electric Car*, 24-25.

[57] U.S. Public Law 94-413, 94th Cong., 2d sess. (17 September 1976), *Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976*.

[58] Maxine Savitz, "The Federal Role in Conservation Research and Development," in *The Politics of Energy Research and Development: Policy Studies 3*, eds. John Byrne and Daniel Rich (New Brunswick, NJ: Transaction Books, 1986), 111.

With the federal government focused on the battery as the prime power source for electric vehicles, little work on automotive fuel cells was done in the 1980s and early 1990s. The Belgian firm ELENCO explored alkaline technology before terminating its program in 1995. In the United States, the Department of Energy and the Federal Transit Administration sponsored a program at Georgetown University to retrofit several buses with electric drive and phosphoric acid fuel cell powerplants beginning in 1988.[60] Not until the mid-1990s was there renewed interest in fuel cell electric drive passenger vehicles. This stemmed from a variety of material and socio-economic and political factors. As we will see later, the improvement of the membrane fuel cell by Ballard Power Systems represented the key technological development. But it was the decision of the California government in 1990 to force the automobile industry to produce electric vehicles as a solution for the state's air pollution problem that created the political conditions necessary for a massive increase in research on the fuel cell automobile. As carmakers fought the legislated production of electric vehicles, arguing storage battery technology did not provide sufficient capacity to give the long range that consumers demanded, the fuel cell appeared to all parties as an acceptable compromise: a power source that would finally make the electric vehicle the equal of the internal combustion engine automobile, only far cleaner.

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[59] Kirsch, *The Electric Vehicle and the Burden of History*, 204-206.

[60] Department of Transport, Federal Transit Authority, "Fuel Cell Transit Bus: Fuel Cell Technology Development and Demonstration," http://www.fta.dot.gov/2422_7250_ENG_Printable.htm, accessed 4 May 2005.

"Power to Change the World:" Ballard and the Automotive Fuel Cell Boom

Until the late 1980s, fuel cell technology had almost no public profile in the United States. The only model anywhere near commercial readiness, UTC's PC-25, was a utility generator competing in a small market. In the early 1990s, Ballard Power Systems, through its partnership with the German auto giant Daimler-Benz, played a leading role in making fuel cells a household name. As with General Electric, idealized demonstrations were both Ballard's lifeblood and its Achilles' heel. They were a vital means of raising research capital during Ballard's formative years, but also set up a future reckoning with the physical limitations of fuel cell technology and infrastructure, issues intimately bound up in the willingness of the company's sponsors to invest in it. Though Ballard's official corporate strategy had always focused on developing stationary and portable electrical generation as well as automobile fuel cell applications, its marketing ideology, the material requirements of fuel cell research and development and the technopolitical goals of its prime sponsors made the automotive application increasingly important to the company's ability to sustain itself after 1997.

Automotive and utility fuel cell applications have different kinds of requirements. Stationary generation requires lifetimes of up to 40,000 hours. Infrastructure poses less of a problem in such applications since utility fuel cells typically employ methane and can thus be easily integrated into the natural gas grid. In some ways, the situation is reversed with automotive fuel cells. Such powerplants require much shorter lifetimes, typically between 4000 to 5000 hours, and a high power-to-weight ratio. This does not mean that the technical issues are simpler. Automotive fuel cells, like all fuel cell systems, require fuel storage or processing technology before they can be considered practical. These vary depending on the type of fuel that is used, which in turn carries important implications for on-board vehicle systems and for infrastructure. If hydrogen is used, it becomes necessary to develop a means to produce and distribute hydrogen and store it in a vehicle. If a hydrocarbon is used, it must be converted into hydrogen either inside or outside the vehicle through the use of reformer technology.

As with Bacon, Ballard, in its initial work with fuel cells, had not considered specific applications and their implications for cost and infrastructure. The company's involvement with the technology was largely the result of an abiding interest within the Canadian military industrial complex in fuel cells as a potential replacement for batteries. In 1983, the Canadian Defence Research Establishment Ottawa (DREO) issued a request for proposal for a membrane fuel cell, a technology originally developed by General Electric for space and terrestrial purposes. Ballard, then manufacturing batteries for the U.S. military, responded. The result was a contract for three prototype membrane fuel cells, beginning a relationship with the Canadian Department of National Defense that provided Ballard with the bulk of its income between 1983 and 1989.[61] Funding remained a constant concern for Ballard in this capital-intensive field. The company did not focus on any specific applications in its first years of operation, concentrating instead on improving the power output of laboratory fuel cells.[62] During this period, it derived income from sales of conventional batteries to the U.S. Army and from the contract with the Canadian government. However, by the end of the decade, this revenue was inadequate to cover research costs. In 1989, Ballard Power Systems decided to forgo niche applications and seek mass markets in stationary and automotive applications.[63]

Though Ballard saw utility fuel cells as the largest early market, its conduct of research and development was shaped primarily by the clash between local and national industrial and political interests triggered by passage in 1990 of the Zero Emission Vehicle law by California's Air Resources Board (CARB), controlled directly by the state's executive branch. This required automakers to produce and market a quota of zero emission vehicles in increasing proportions if they wished to do business in California.[64] A remarkable piece of legislation in the annals of government regulation of private industry, it was driven by the state's political and business elites on the assumption that large numbers of electric passenger vehicles could not only end intolerably high air pollution but also revive an armament-dependent economy that had sunk into recession at the end of the Cold War.[65] Conversely, the oil and automobile industries, long hostile to the battery electric passenger vehicle, bitterly resisted the ZEV law. They devoted millions of dollars lobbying the CARB to roll back the quota deadlines, arguing that early introduction of underdeveloped battery electric vehicles would cause consumers to reject them, undermining the entire initiative.[66]

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[61] Tom Koppel, *Powering the Future: The Ballard Fuel Cell and the Race to Change the World* (Toronto: John Wiley & Sons Canada, Ltd., 1999), 64.

[62] While Ballard had little experience in fuel cells, it was not wholly without resources as it moved into the new field. Its program received a major boost from small basic research projects underway at Texas A&M University and the Department of Energy's Los Alamos National Laboratories in the mid-1980s. These focused on reducing the quantity of costly platinum required by acidic low-temperature fuel cells, long the major weak point of such devices. In principle, this made the technology commercially viable; A.J. Appleby, "The Electrochemical Engine for Vehicles," *Scientific American* 281, no. 1 (July 1999): 75.

[63] The journalist Tom Koppel reports that Ballard's principals had harbored hopes for automotive applications from at least the mid-1980s. He noted the impression Ballard's improvements to the membrane fuel cell made on Byron McCormick, head of the Department of Energy's fuel cell division at Los Alamos National Laboratories in the mid-1980s. Koppel, quoting David McLeod, then Ballard's marketing manager, reports that at a conference in Arizona in 1986 during which Ballard officials announced that they had improved current density by a factor of four, McCormick remarked to McLeod that his company had "just made the electric vehicle possible." McCormick left Los Alamos shortly thereafter to head General Motors' automotive fuel cell program. Koppel notes that Ballard's decision to forgo niche power source markets in 1989 was largely the work of Michael Brown, a Vancouver venture capitalist, and Firoz Rasul, Geoffrey Ballard's replacement as chief operating officer in 1989. Brown reasoned that though these applications might raise more revenue in the short-term, they would detract Ballard from its "end target," large stationary generators and, above all, automotive power. He told Koppel that they "knew the endgame was the car;" Koppel, *Powering the Future,* 94, 126-128.

Fuel cell technology enabled the reconciliation of these conflicting interests in a way that battery technology could not. For decades, researchers and their sponsors perceived the fuel cell as an efficient, long-lived and clean electrochemical engine able to use common fuels. In the techno-political environment of the 1990s, these qualities were especially attractive to a variety of actors. Automakers believed fuel cells would ameliorate short range, the chief handicap of battery electric vehicles, allowing them to reach 480 kilometers, the distance they claimed consumers demanded in an automobile. Oil companies did not see fuel cells as a threat to their business, unlike batteries. As in the 1960s, they hoped to market fuel cell fuels when the technology became widely commercialized. Fuel cell developers like Ballard saw an opportunity to profit from what appeared to them as an impending paradigm shift in automotive power. Finally, as an abundant energy black box, the fuel cell offered a way for government leaders to circumvent the divisive and difficult realm of environmental and energy politics, solving the problem of sustainable transportation in one deft technological stroke.

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[64] The law stipulated that by 1998, two per cent of light-duty cars and trucks sold in the state had to be zero emission vehicles; the quota increased to five per cent in 2001 and 10 per cent in 2003; California Environmental Protection Agency, Air Resources Board, "The Zero Emission Vehicle Program," http://www.arb.ca.gov/msprog/zevprog/factsheets/zevprogam.pdf, accessed 12 February 2007.

[65] See Kirsch, *The Electric Vehicle and the Burden of History*, 206; Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age*, 273; John M. DiCicco, "The 'Chicken or Egg' Problem Writ Large: Why a Hydrogen Fuel Cell Focus is Premature," in *The Hydrogen Energy Transition: Moving Toward the Post-Petroleum Age In Transportation* eds. Daniel Sperling and James S. Cannon (Burlington, MA: Elsevier Academic Press, 2004),15.

[66] Automotive analyst John M. DeCicco claims the proximate cause of this law was the General Motors Impact battery electric concept vehicle, the forerunner of the EV-1, unveiled in January 1990; DeCicco, "The 'Chicken or Egg' Problem Writ Large: Why a Hydrogen Fuel Cell Focus is Premature," 215, 218.

Ballard's commercial ambitions, intense pressure on automakers to alter their power systems in a time of growing environmental consciousness and the easy availability of venture capital in the technology bubble of the "roaring nineties" combined to foster an atmosphere in which the fuel cell automobile appealed to many as a solution whose time had arrived. Automakers and fuel cell developers, above all, Ballard, staged a series of demonstrations of increasingly powerful and sophisticated fuel cell automobiles and buses throughout the 1990s, all the while intimating to the media that carbonaceous and hydrocarbon fuels could be used interchangeably.[67] This generated demand for the company's pre-commercial automotive fuel cells, which became the company's main source of revenue.[68] As a result, Ballard's renowned

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[67] The use of pure hydrogen as fuel not only made for unproblematic demonstrations, but was central to Ballard's branding of itself as a revolutionary clean energy company.

[68] Between 1994 and 1996, Ballard reported revenue of CAN $63.3 million. In this period, the company had contracts for automotive fuel cells with the Chicago and Vancouver transit authorities ($8 million and $8.6 million respectively), Daimler-Benz ($2.3 million), Honda ($2 million), Volkswagen and Volvo ($1.2 million), General Motors and the U.S. Department of Energy ($6 million) and the U.S. Department of Transport's Federal Transit Administration ($8.1 million). The Canadian Department of National Defense and the German firm Howaldtswerke-Deutche Werft (HDW) had contracts with Ballard for submarine fuel cells worth $3.7 million and $9.3 million respectively. Finally, Ballard had revenue from its battery division totaling $8.64 million ($2.64 million from the sale of batteries and $6 million from the sale of the battery division itself in 1995); see

"green" ethos, which posited the membrane fuel cell as a technological solution to the environmental crisis, became associated almost entirely with the electric passenger automobile, the only fuel cell application with the potential for sufficiently large sales volumes to have an appreciable effect on noxious emissions, at least in theory.

"The Non-Battery Electric Vehicle:" Fuel Cell Automobile Demonstrations and Green Technopolitics

To a large extent, Ballard's fortunes have been shaped by Daimler-Benz, one of the world's most prestigious automotive houses and a company with an interest in hydrogen propulsion technology dating to the 1970s.[69] In keeping with the historical trends, this relationship turned on Ballard's ability to rapidly improve the power density of its fuel cells throughout the 1990s. With the turn of the millennium, the partnership would face a crisis of expectation over the issues of durability and fuel production and storage. The heart of Ballard's case for fuel cells was that, unlike electrical storage devices, which had limited capacity and long recharging periods, they could "produce" power indefinitely as long as fuel was supplied. This was misleading. While Ballard periodically released data on improvements in the power output of its membrane fuel cells, it was much less forthcoming with information on durability.[70]

Ballard Power Systems, Inc., *Annual Report 1996* (1997), 21-25. Ballard's major source of revenue remained pre-commercial automotive fuel cell powerplants for demonstration programs into the mid-2000s. The company did not develop a large stationary fuel cell generator for field trials until mid-1997 and did not begin sales of pre-commercial demonstrators for trials until 1999; see Ballard Power Systems Inc., *Annual Report 1999* (2000), 26.

[69] Daimler-Benz experimented with hydrogen-fuelled internal combustion engines in a number of vehicles in the mid-1970s; see Peter Hoffmann, *The Forever Fuel: The Story Of Hydrogen* (Boulder, CO: Westview Press, 1981), 119-124.

[70] Ballard Power Systems, product brochure and press release, 9 January 2000. Review papers assessing Ballard fuel cells typically focused on current density, rarely mentioning fuel cell lifetimes; for example, see Keith B. Prater's "Polymer Electrolyte Fuel Cells: A Review of Recent Developments," *Journal of Power Sources* 51 (1994): 129-144; 172-173; Stone and Morrison, "From Curiosity to 'power to change the world,'®," 1-13.

Further, Ballard specialized in developing the fuel cell energy converter, not the auxiliary technologies needed to store, produce or process fuel for electric automobiles. Historically, reformers had lagged behind fuel cell technology, a pattern that continued in the 1990s.[71] Though reforming technology dated from the early 1960s, by the mid-1990s they were practical only for large utility fuel cells, where miniaturization was less important. Similarly, hydrogen storage technology is much more difficult to develop for a passenger automobile than for other applications. Nevertheless, for years Ballard claimed in its annual reports that fuel cells in general were capable of using a variety of fuels equally well, including hydrogen, methane, methanol and gasoline, while saying little about the comparative technical and infrastructure requirements of stationary and vehicular applications and the electrochemical consequences of these fuels.[72] Advances in the fuel cell powerplant itself, above all current density, would far outpace those in automotive fuel systems throughout the 1990s and in the 2000s. Consequently, Ballard's ability to commercialize its fuel cells depended on the external technological, economic and political developments relating to the struggle between industrial and political forces in California and the eastern U.S.

Ballard first applied automotive fuel cell technology in buses, the first of which was tested in Vancouver in 1993. In the mid-1990s, Ballard went on to develop fuel cell powerpacks for a small number of electric buses for demonstration fleets in

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[71] Steven G. Chalk et al., "The US Department of Energy-Investing in Clean Transport," *Journal of Power Sources* 71 (1998): 29.

[72] Ballard abandoned the multi-fuel claim in its 2001 annual report, released in early 2002. Similarly, the company did not cite fuel as a factor under "Risks and Uncertainties" until its 2002 annual report, released in early 2003. Ballard then stated that hydrogen was the only suitable fuel and that unless third parties invested in a hydrogen infrastructure, a mass market for fuel cell electric vehicles was unlikely to develop; Ballard Power Systems, Inc., *2001 Annual Report* (2002), 17, *2002 Annual Report* (2003), 44-45.

Vancouver and Chicago.[73] Though these programs did much to raise the company's profile as a maker of a "green" automotive power source, Ballard always viewed the passenger automobile as its most important market. In 1992, the company attracted the attention of Daimler with its Mk 5 stack, then its most advanced model. Producing 150 watts per liter or kilogram, this was one of the most powerful fuel cells of the day, with 30 times the power density of General Electric's Gemini fuel cell. At $60,000 per kilowatt, the Mk 5 was almost as expensive.[74] In 1992, the Canadian firm leased a Mk 5 to the German automaker for evaluation, leading to a four-year deal signed in 1993 to build a fuel cell demonstration automobile.[75] This collaboration produced the NextCar (NECAR) I, unveiled in April 1994. Based on a van chassis and powered by hydrogen fuel cells, this vehicle was not much more practical than General Motors' 1960s-era Electrovan. Like that of its predecessor, the interior of the NECAR I was entirely filled with the fuel cell stack and its hydrogen fuel tank.

At over 4300 kilograms, this vehicle was considerably heavier than the Electrovan.[76] Nevertheless, Oscar Suris of the *Wall Street Journal* hailed the demonstration as a "breakthrough" in vehicle technology. Referring to the NECAR I as a "non-battery electric vehicle," it cited Daimler's claim that it had solved all the fundamental technical problems and that the fuel cell could easily use hydrogen converted from methanol with the aid of an on-board reformer. Suris also suggested that the test could increase pressure within the Partnership for a New of Generation of Vehicles (PNGV) to place more emphasis on fuel cells.[77] This proved prescient. Initiated by the Clinton administration in September 1993, the PNGV was a collaborative research and development effort between American automakers and the federal government to produce efficient and clean automobile power sources. It aimed to triple the fuel economy of the average 1994 passenger sedan from 26.6 miles per gallon (11.3 kilometers per liter) to 80 miles per gallon (34 kilometers per liter) by 2004. Given this ambitious objective and limited time frame, stated PNGV managers, only the most advanced powertrain technologies, including fuel cells, would be considered.[78]

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[73] Stone and Morrison, "From Curiosity to 'Power to Change the World®,'" 5-7. Koppel reports that Ballard claimed that the company's 1993 bus demonstration had been conceived by he and British Columbia energy minister Jack Davis. According to Ballard, Davis agreed to provide funds in exchange for a "green photo-op" to help boost the sagging political fortunes of then-Premier William Vander Zalm (148).

[74] A.J. Appleby, "Issues in Fuel Cell Commercialization," *Journal of Power Sources* 69 (1996): 172.

[75] In the early 1990s, Ballard, Daimler-Benz and the U.S. Department of Energy determined that an automotive fuel cell needed much greater power density than that afforded by the Mk 5, in the range of 500-1000 watts per kilogram; Keith B. Prater, "Polymer Electrolyte Fuel Cells: A Review of Recent Developments," *Journal of Power Sources* 51 (1994): 138.

[76] John M. DeCicco, *Fuel Cell Vehicles: Technology, Market and Policy Issues* (Warrendale, PA: Society of Automotive Engineers, Inc., 2001), 72.

The PNGV accords well with Langdon Winner's observations of the attractions of technology over traditional politics to U.S. leaders.[79] American automakers had long opposed federal efforts to legislate fuel efficiency and fought the Corporate Average Fuel Economy (CAFE) standard ever since it was established through the Energy Policy and Conservation Act of 1975. They had powerful allies in Congress, particularly after 1994, when the Republican Party obtained control of the House of Representatives as a result of the mid-term elections of that year. The logic of the PNGV was that with fuel prices at record lows, consumers had no incentive to purchase fuel-efficient vehicles. If the PNGV could achieve its goals without compromising the comfort and performance of passenger automobiles, "market forces," that is, consumer preference for an objectively superior product, would bring about higher national fuel efficiency without the need for legislating technological change.[80]

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[77] Oscar Suris, *The Wall Street Journal.* 'Daimler-Benz Unveils Electric Vehicle, Claiming a Breakthrough on Fuel Cells,' 14 April 1994, p. B2.

[78] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles* (Washington, D.C: National Academy Press, 1994), 12-13.

[79] Langdon Winner, *Autonomous Technology: Technics Out-of-Control as a Theme in Political Thought* (Cambridge, MA: MIT Press, 1977), 237.

Work on fuel cells within the PNGV began in mid-1994. Its members took a dual approach to fuel cell fuel systems. The Department of Energy supported both an on-board methanol reformer developed by General Motors and hydrogen systems developed by Ford and Chrysler.[81] Three months after the demonstration of NECAR I, Ford and Chrysler received their first federal contracts for automotive fuel cells under the PNGV, worth $13.8 and $15 million respectively.[82] In the meantime, Daimler-Benz and Ballard worked to produce a hydrogen-fuelled successor to the NECAR I. In May 1996, they rolled out the NECAR II at Berlin's Brandenburg Gate. The electric van had room for six passengers and was hailed by the media as a major technical and aesthetic advance over its test-bed predecessor. In the wake of the publicity generated by NECAR II, the Daimler/Ballard partnership did little to discourage the impression that the fuel cell was a kind of universal chemical energy converter, an idea soon taken up by the media. Concentrating on the fuel cell vehicle's environmental qualities, press reports often blurred the crucial distinction between all-hydrogen and reformed-fuel systems. Nick Nuttall, the *Times of London*'s technology correspondent, claimed that fuel cells operated equally well on any hydrogen-rich fuel including liquid hydrogen, methanol, ethanol and gasoline. Gary Acres, a scientist with platinum supplier Johnson Matthey, declared that NECAR II "signaled the end of the internal combustion engine."[83] Ferdinand Panik, Daimler's head of fuel cell research, lent further authority to the idea that technical and infrastructure problems had largely been solved, stating the company planned to market "a minimum" of 100,000 fuel cell vehicles in eight years.[84]

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[80] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Sixth Report* (Washington, D.C.: National Academy Press, 2000), 14-15. These were important considerations in the U.S. techno-polity. At first glance, the PNGV conflicted with the agenda of American automakers. The program's architects ignored the fact that U.S. automakers were less interested in commercializing efficient passenger sedans at a time when record low gasoline prices made the sports utility vehicle an economically viable and highly profitable product. As a government-funded research project with no legal requirement to produce any of the new technologies that might emerge, the PNGV was acceptable to the auto industry. Jeffrey Ball of *The Wall Street Journal* reported that the automakers had agreed to participate in the PNGV on condition that the federal government not tighten existing fuel efficiency legislation; see Jeffrey Ball, "Bush Shifts Gears on Car-Research Priority," *The Wall Street Journal*, 9 January 2002, p. C14.

[81] Steven G. Chalk et al., (U.S. Department of Energy), "The New Generation Of Vehicles: Market Opportunities for Fuel Cells," *Journal of Power Sources* 61 (1996): 10.

[82] *The Wall Street Journal*, "Ford, Chrysler Win Auto Fuel-Cell Work," 13 July 1994, p. B2.

Ballard became firmly bound to the interests of the auto industry after it invested heavily in the company in 1997. In April, Daimler purchased a 25 per cent stake in Ballard worth $500 million. Four months later, the partners unveiled the NECAR III demonstration automobile. Based on the chassis and body of the Mercedes A-class compact car, it was the first fuel cell vehicle employing a methanol reformer, though the unit occupied most of the usable passenger and cargo space. In December, Ford made a $500 million investment in Ballard and Ford executives heaped praise on fuel cells. Chairman Alex Trotman referred to them as "one of the most important technologies of the early twenty-first century."[85] William Clay Ford, Jr., the chairman of the company's finance committee, suggested fuel cells had finally made the electric drive passenger vehicle practical.[86]

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[83] Nick Nuttall, "Breathtaking…the vehicle powered by air," *The Times of London*, 15 May 1996, p. 7.
[84] Brandon Mitchener and Tamsin Carlisle, "Daimler, Ballard Team to Develop Fuel-Cell Engine," *The Wall Street Journal*, Tuesday, 15 April 1997, p. B8.
[85] Valerie Reitman, "Ford is Investing in Daimler-Ballard Fuel Cell Venture," *The Wall Street Journal*, 16 December, 1997, p. 1.
[86] Anthony DePalma, "Ford Joins in a Global Alliance to Develop Fuel-Cell Auto Engines," *The New York Times*, 16 December 1997, p. D1.

In March 1999, Daimler, by then DaimlerChrysler, chose Washington, D.C. as the backdrop for the American debut of a Ballard fuel cell-powered vehicle. This was the NECAR IV, billed as the first fuel cell automobile to be driven on public roads in the United States.[87] Based on the DaimlerChrysler A-class, NECAR IV, claimed company chairman Juergen Schrempp, proved the technical feasibility of fuel cell vehicles. Future work, he added, would focus on reducing costs.[88] Environmental Protection Agency Administrator Carol Browner hailed the vehicle as a "real step forward," noting that its only effluent was water vapor. But NECAR IV was not unique among hydrogen fuel cell demonstration vehicles in possessing this quality.[89] In a retrogression in the company's design thrust towards methanol, the vehicle employed liquid hydrogen storage. Although this afforded a range of 450 kilometers, making it the longest-legged of all DaimlerChrysler's demonstration vehicles to date, liquid hydrogen is an exotic fuel that is costly to produce and difficult to store.[90] This one-off feature, not emulated in any subsequent fuel cell electric demonstration vehicle, did remedy the problem of short range, the auto industry's chief complaint against battery electric vehicles.

One month later, industry voted its confidence in the fuel cell passenger automobile with the inauguration of the California Fuel Cell Partnership (CAFCP). Comprising DaimlerChrysler, Ford, Ballard Power Systems, Shell, Texaco, Atlantic

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[87] In fact, the first fuel cell electric automobile to operate on U.S. public roads debuted in April 1998. This was a Danish Kewet two-seat battery electric car converted to fuel cell power by Humboldt State University's Schatz Energy Research Center, a project funded the Department of Energy, California's South Coast Air Quality Management District and the southern California city of Palm Desert.

[88] "DaimlerChrysler Presents First Drivable Fuel Cell Technology Car in the U.S.," DaimlerChrysler press release, 17 March 1999.

[89] DePalma, D1.

[90] John M. DeCicco, *Fuel Cell Vehicles: Technology, Market, and Policy Issues* (Warrendale, PA: Society of Automotive Engineers, Inc., 2001), 73.

Richfield and the State of California, the CAFCP was intended to test new technology, develop product codes and standards and educate consumers in preparation for the commercialization of fuel cell electric passenger vehicles.[91] By the early 2000s, it would become the world's largest fuel cell vehicle/infrastructure demonstration project.

The CAFCP can be interpreted as the capstone of the auto industry's campaign against the legislated mass production of battery electric passenger vehicles. Between 1991 and mid-1995, car and oil companies spent $34 million lobbying the California legislature to roll back the ZEV quotas. In 1996, the CARB eliminated the quotas for 1998 and 2001. In exchange, a Memorandum of Agreement was drafted committing the largest automakers to produce 1800 battery electric vehicles between 1998 and 2000. In December 1996, General Motors began to offer the EV-1 electric coupe, derived from the company's Impact concept vehicle, for lease in California and Arizona. Between 1997 and mid-2000, industry spent a further $32 million pressuring the Governor's Office to eliminate the 2003 quota, obtaining another concession from the CARB in 1998. Only four per cent would have to be zero-emission vehicles, while the other six per cent could be very low emission vehicles, such as methanol fuel cell electrics, which could get partial credit under the zero emission vehicle system.[92]

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[91] Alan C. Lloyd, (California Air Resources Board), "The California Fuel Cell Partnership: An Avenue to Clean Air," *Journal of Power Sources* 86 (2000): 57.

[92] Brad Heavner, *Pollution Politics 2000: California Political Expenditures of the Automobile and Oil Industries, 1997-2000* (Santa Barbara, CA: California Public Interest Research Group Charitable Trust, 2000), 7-8. The industry's anti-ZEV efforts comprised direct lobbying of the California state government and campaign contributions to anti-ZEV political candidates. Interestingly, as the car companies negotiated with the CARB in late 1995, they offered to produce a total of 5000 battery electric vehicles by late 1996 and early 1997, well before the 1998 deadline, and 14,000 in 1998. In exchange, the quota of 22,000 zero emission vehicles for that year was to be scrapped; Marla Cone,

Putting the Cart Before the Horse: Fuel Infrastructure and Automotive Fuel Cell Systems

In backing the creation of the CAFCP, the auto industry essentially declared fuel cell electric drive more technically and economically feasible than battery electric drive. Yet by the turn of the millennium, General Motors had manufactured hundreds of battery electric EV-1s and leased them to customers, while the auto industry's various fuel cell electric vehicle programs had barely gotten underway. Only a handful of demonstration automobiles had been produced and cost and reliability needed to be dramatically improved.[93] Most importantly, the fuel question, on which the viability of the scheme ultimately rested, remained unresolved.

Daimler and Ballard favored methanol, a fuel they believed would facilitate early commercialization on the assumption that it could be seamlessly introduced into the infrastructure. However, some researchers questioned this, noting that the alcohol was so corrosive that existing fuel production and distribution systems were likely to require major modifications in order to handle it. What was more, methanol proved much less efficient than hydrogen when used directly in fuel cells. Not only was more platinum required to drive the electrochemical reaction, owing to methanol's lower

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"Board to Ease Mandate to Build Electric Cars," *Los Angeles Times*, 17 November 1995, p. A3. This contradicted the auto industry's argument that premature introduction of battery electric automobiles would destroy consumer confidence in such vehicles. David Kirsch also notes this "odd twist" in the negotiating position of the automakers, though makes no further comment; *The Electric Vehicle and the Burden of History*, 207.

[93] In 1997, the proton exchange membrane alone cost between $400-$1000 per kilowatt, or $50-$70 per square foot. This had to be reduced to between $5-$15 per square foot for fuel cell electric automobiles to be commercially viable; David P. Wilkinson and Alfred E. Steck, "General Progress in the Research of Solid Polymer Fuel Cell Technology at Ballard," in *Proceedings of the Second International Symposium on New Materials for Fuel Cell and Modern Battery Systems: New Materials for Fuel Cells and Modern Battery Systems II, Montréal, Canada 6-10 July 1997*, eds. O. Savadogo and P.R. Roberge (Montréal: École Polytechnique de Montréal, 1997), 32.

reactivity, direct methanol fuel cells still suffered from the same problem of premature cathodic oxidation that had plagued the technology since the 1960s.[94]

Between 1996 and 2000, the PNGV's focus in fuel reforming shifted from methanol to gasoline and then to multi-fuel reforming, each progressively a much more technically demanding process.[95] A gasoline reforming experiment sponsored by the Department of Energy in fall 1997 was heralded by Energy Secretary Federico Peña as a "terrific breakthrough" on the road to non-battery electric drive.[96] However, the test, which involved only a single Ballard cell over a period of 16 hours, was hardly a realistic indication of how a miniaturized gasoline reformer-fuel cell system would behave over the expected lifetime of an automobile. While fuel cell-related work comprised the second largest single area of expenditure in the PNGV after hybrid propulsion systems, funding had been declining since 1995, averaging around $22 million per year. Beginning in late 1997, this trend reversed and the PNGV's fuel cell spending grew much more rapidly thereafter, climbing to almost $30 million by 1999.[97]

Changing priorities in the fuel reforming program led to contradictions in the Daimler/Ford/Ballard program. Fearing that the petroleum industry was unlikely to invest willingly in a methanol infrastructure, Daimler began to collaborate in early 1998 with General Motors, Chrysler and United Technologies in developing gasoline reformer technology.[98] By investing in two fuel reformer systems, the company hedged on the question of the ultimate system its pre-commercial vehicle prototypes would employ. While the methanol-fuelled NECAR III ostensibly represented the state of the art, Daimler continued to employ the hydrogen-fuelled NECAR II in public demonstrations.[99] However, the hydrogen fuel cell and the multi-fuel reformer/fuel cell systems had considerably different operating characteristics and infrastructure requirements, a distinction typically ignored by media market pundits.

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[94] Christopher E. Borroni-Bird, "Fuel Cell Commercialization Issues for Light-Duty Vehicle Applications," *Journal of Power Sources* 61 (1996): 42. Exxon researchers believed that developing a methanol infrastructure could cost between $15-$30 billion; Paul J. Berlowitz and Charles P. Darnell, "Fuel Choices for Fuel Cell Powered Vehicles," *Fuel Cell Technology for Vehicles*, 50.

[95] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Second Report*, (Washington, D.C: National Academy Press, 1996), 53-54; National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Third Report*, (Washington, D.C.: National Academy Press, 1997), 65; Steven G. Chalk et al., (Department of Energy), "Challenges for Fuel Cells in Transportation Applications," *Journal of Power Sources* 86 (2000): 44.

[96] Matthew L. Wald, "In a Step Toward a Better Electric Car, Company Uses Fuel Cell to Get Energy From Gasoline," *The New York Times*, 21 October 1997, p. A14.

[97] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Sixth Report*, 76.

Throughout this period, the fortunes of the fuel cell electric vehicle in general, and Ballard in particular, were firmly tied to the evolving technopolitical battle between automakers and the CARB on the one hand, and between American and Japanese automakers on the other. The automobile industry was of one mind regarding the undesirability of battery electrics. Virtually all the major carmakers produced small numbers of such vehicles, mostly for lease, before ending these programs in the early 2000s.[100] This left the hybrid gasoline electric powerplant as the only near-term

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[98] Stuart F. Brown, *Fortune*, 30 March 1998, 122 [D]; DeCicco, *Fuel Cell Vehicles*, 57.

[99] Daimler-Benz invited *Fortune*'s Brown to test drive the NECAR II March 1998 even as the company touted its methanol-fueled successor.

[100] By 2001, there were about 3000 battery electric passenger vehicles operating in California. Beginning in 1996, General Motors offered the EV-1 for lease in California and Arizona, building around 1000 before halting production in 2000; Westbrook, 136. Ford produced a similar number of Th!nk City cars, offering them for lease starting in 2001 in California, New York, Michigan, Georgia and Europe; James Francfort and Vicki Northrup, *Th!nk City Electric Vehicle Demonstration Program: Second Annual Report 2002-2003* (Department of Energy, 2004), 1; In 2003, the CARB postponed ZEV quotas until the end of the decade, effectively marking the end of commercial battery electric vehicle programs. In 2004, the American automakers began recalling these vehicles and destroying them. After heavy lobbying by Greenpeace, 300 Ford Th!nk City automobiles were made available for sale through Ford dealerships in Norway; www.greenpeace.org/norway/news/basckground-on-think-electric-vehicles, www.greenpeace.org/international/news/th-nk-again-ford-does-a-u-turn, accessed 22 February, 2007.

"near-zero emission vehicle." Despite six years of government-backed research through the PNGV, American automakers failed to commercialize this technology; Japanese manufacturers, on the other hand, had two: Toyota's Prius and Honda's Insight, both of which appeared on the U.S. market in 2000. While production volumes were relatively small, these programs were potent symbols of green technological virtuosity, particularly after the automakers stopped producing battery electric vehicles. Consequently, the fuel cell automobile became the U.S. auto industry's leading ZEV candidate in the public relations battle for the mantle of environmental leadership, particularly given its heavier reliance on trucks and sport utility vehicles in comparison with its Japanese counterpart.

With the turn of the millennium, however, expectations began to founder on the technical and economic realities attending the use of gasoline and methanol in reformer-fuel cell systems. During the 1990s, Ballard made impressive progress in boosting the current density of its hydrogen fuel cells, achieving the PNGV benchmark of 1000 watts per liter by mid-1995.[101] Perfecting a cheap and reliable carbonaceous fuel cell system for passenger vehicles was a completely different matter. This automotive application was the most demanding and complex of all fuel cell roles. Described by some researchers as a "miniature chemical plant," the reformer-fuel cell power train had to convert carbonaceous fuel to hydrogen,

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California Environmental Protection Agency, Air Resources Board, "The Zero Emission Vehicle Program," http://www.arb.ca.gov/msprog/zevprog/factsheets/zevprogam.pdf.

[101] The progress of Ballard's improvements in current density during the 1990s forms an s-curve. From 1989 to 1997, the company dramatically increased the power of its fuel cells. Between 1989 and 1992, current density was boosted from 85 to 140 watts per litre. From 1992 to 1994, current density doubled from 140 to 290 watts per litre. It nearly doubled again between 1994 and 1995 to 570 watts per litre and then again between 1995 and the middle of 1996 to 1000 watts per litre. Thereafter, advances came at a much slower rate; current density was boosted by only 20 per cent, to 1200 watts per litre at the end of 1997 and by a little over ten per cent between the end of 1997 and 2000 to 1310 watts per litre; Stone and Morrison, "From Curiosity to 'power to change the world,'®," 7-8.

distribute it evenly to all cells, remove waste water and perform all of these functions almost instantaneously in response to demand for power. As in the 1960s, fuel cells remained especially vulnerable to sulfurous fuels.[102] By 2000, the PNGV partners had not developed a viable automotive fuel reformer of any kind. While some progress had been made with methanol reformers, the results were disappointing. Arthur D. Little, the main reformer contractor, acknowledged in 1999 that methanol fuel cell electric vehicles could not yet be "cold-started," requiring up to 30 minutes to warm up before they could be driven.[103]

Moreover, some observers had doubts whether the massive use of methanol would be feasible in California, where public opinion was highly sensitive to groundwater contamination from the gasoline additive methyl tertiary butyl ether (MTBE).[104] Like MTBE, methanol is readily miscible with water and highly toxic. By 2000, industry analysts were suggesting that hydrogen was the only practical fuel cell fuel. That year, Arthur D. Little released a study suggesting that "off-board" fuel reforming might be preferable to miniaturized automobile chemical plants.[105] The National Research Council reached a similar conclusion. Noting the gasoline reformer was impracticable given the state of the art, it recommended the PNGV consider ways to produce hydrogen from natural gas or gasoline at existing service stations.[106] By 2003, all the major automakers had ended work on on-board reformers and focused instead on hydrogen fuel cell systems.[107] This meant that hydrogen production and distribution infrastructure would be necessary to commercialize fuel cell electric passenger vehicles, a project that, in turn, required government intervention. For a time in the early 2000s, it seemed as if the U.S. federal government was committed to building such a system.

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[102] Westbrook, *The Electric Car*, 184-185, DeCicco, *Fuel Cell Vehicles*, 54-57. Integrating reformers with a fuel cell had historically proved extremely difficult. It was true that the first fuel cell to be commercialized, United Technologies Corporation's PC-25, employed a fuel reformer system. But it required almost 30 years and tens of millions of federal dollars to perfect this phosphoric acid utility fuel cell system. The technical complexity of that project had been eased somewhat by the fact that reformers did not have to be miniaturized for fuel cell systems for large vehicles and stationary generators as they did for passenger sedans.

[103] Richard K. Stobart (Arthur D. Little), "Fuel Cell Power for Passenger Cars-What Barriers Remain?" *Fuel Cell Technology for Vehicles*, 14. An additional problem was posed by methanol's unusual qualities. Because this alcohol burns with an invisible flame, a luminosity agent would probably have to added before the fuel could become widely commercialized. Such additives promised to place additional stress on the catalytic reformer, shortening the lifetime of the system.

[104] DeCicco, *Fuel Cell Vehicles*, 61.

[105] Sean Casten, Peter Teagan and Richard Stobart (Arthur D. Little), "Fuels for Fuel Cell-Powered Vehicles," *Fuel Cell Technology for Vehicles*, 61-62.

Fuel Cell Technopolitics and The Hydrogen Economy

The fruits of the PNGV were displayed at Detroit's annual auto show in January 2000. Of the consortium members, General Motors was the only one to produce a fuel cell concept vehicle.[108] Its entry, the "Precept," was actually two cars. One was an advanced gasoline hybrid while the other used a hydrogen fuel cell. Both, claimed the company, got 108 miles per gallon, well above the PNGV goal. GM's Vice Chairman Harry Pearce used the occasion to announce the new direction of the company's alternative automotive program. Citing low demand, the company cancelled the EV-1 battery electric vehicle program. General Motors had tried to bring the pure battery electric vehicle to market but consumers, said Pearce, had rejected them. The automobile of the future, he said, would be a hybrid and, ultimately, a fuel cell electric using pure hydrogen.[109]

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[106] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Sixth Report*, 85-87.

[107] National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs* (Washington, D.C.: The National Academies Press, 2004), 27.

[108] Daimler inherited Chrysler's PNGV work following their corporate merger in 1998, but this seems to have been kept separate from Daimler/Ballard's fuel cell automobile program. DaimlerChrysler's PNGV electric concept vehicle, the ESX3, employed a battery, not a fuel cell; National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Sixth Report*, 66-67.

This represented an important change in General Motors' philosophy of automobile technology. Prior to the Precept, the company had devoted relatively little effort to fuel cell vehicle demonstration programs. Throughout the 1990s and into the early 2000s, Daimler's Ballard-powered NECARs had dominated the limelight. But after 2000, General Motors became a leading champion of the fuel cell automobile, promoting a series of sophisticated and expensive purpose-built fuel cell demonstration vehicles and promised to be the first automaker to produce a million fuel cell automobiles. The company also began purchasing stakes in companies that made hydrogen production and storage systems. In 2001, it signed a 25-year partnership with Vancouver's General Hydrogen, a company founded by Geoffrey Ballard.[110]

These developments were paralleled by the Bush administration's announcement of FreedomCAR and the Hydrogen Fuel Initiative in 2002 and 2003. These programs were packaged as a federal commitment to build a fuel cell automobile-based hydrogen economy. They were the culmination of a gradual shift in government attitudes towards fuel cells and primary sources of hydrogen supply during the 1990s. The passage in Congress of the Spark M. Matsunaga Hydrogen Research, Development and Demonstration Program Act in November 1990 represented a commitment to sustainable hydrogen production, at least on paper. The act prioritized renewable hydrogen production techniques in small-scale demonstration programs, authorizing $20 million between 1992 and 1994.[111] At first glance, the Energy Policy Act of 1992 seemed to bolster this trend. It authorized "at least one" research and development program devoted to renewable hydrogen energy systems over a period of five years "in accordance" with the Spark M. Matsunaga Act. However, the 1992 act's section on fuel cells supported the development of *hydrocarbon*, not hydrogen systems, allocating $51.5 million in fiscal year 1993 and $56 million in fiscal year 1994.[112]

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[109] Gregory L. White, "GM Stops Making Electric Car, Holds Talks With Toyota," *The Wall Street Journal*, 12 January 2000, p. 1.
[110] Matthew L. Wald, "Another GM Investment in Fuel Cell Development: A Hydrogen Approach to Electric Cars," *The New York Times*, 14 June 2001, p. C10.

The Hydrogen Future Act of 1996 reflected bipartisan political interest in hydrogen. The Act increased overall funding for hydrogen production and conversion systems to $164.5 million over six years, money that was aimed at bolstering the private sector's ability to "demonstrate the technical feasibility" of hydrogen in industrial, residential, transportation and utility applications.[113] It also repealed the renewable hydrogen section of the Energy Policy Act of 1992 and instead subsumed it under the section dealing with fuel cells. Although the Department of Energy was directed to "prove the feasibility" of hydrogen produced from photovoltaic electricity and solid waste, authorizing $50 million for fiscal years 1997 and 1998, the money was never appropriated.[114]

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[111] Public Law 101-566, 101st Cong., 2d sess. (23 January 1990), *Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Program Act of 1990*, Sec. 104: "Research and Development." The culmination of a decade's worth of lobbying by Matsunaga, Democratic Senator of Hawaii, the Act reflected a Congressional consensus that hydrogen had a potentially important role as a storage medium and that effort had to be devoted to reducing production costs if new applications were to be found; *Congressional Quarterly Almanac*, Volume XLVI, 1990, 101st Congress, 2d sess. (Washington, D.C.: Congressional Quarterly Inc., 1991), 318.

[112] Public Law 102-486, 102nd Cong., 2d sess. (24 October 1992), *Energy Policy Act of 1992*, Sec. 2026, "Renewable Hydrogen Energy," Sec. 2115, "Fuel Cells." *Congressional Quarterly Almanac*, Volume XLVIII, 1992, 102nd Congress, 2d sess; (Washington, D.C.: Congressional Quarterly Inc., 1993), 251, 255, 257.

[113] U.S. Public Law 104-271, 104th Congress, 2d sess. (9 October 1996), *Hydrogen Future Act of 1996*, Sec. 103, "Hydrogen Research and Development," Sec. 201, "Integration of Fuel Cells with Hydrogen Production Systems," 110 STAT.3306-3307.

The Act was backed by Republican Representative of Pennsylvania Robert S. Walker and co-sponsored by George E. Brown, the California Democrat whose bills to create a national hydrogen fuel cell program were defeated in the House in 1987. Walker, like Matsunaga and Brown, had promoted hydrogen throughout the 1980s. While Matsunaga supported renewable hydrogen technology, Walker promoted nuclear power and had close ties with the military industrial and aerospace communities. As chair of the House Science Committee, Walker worked with conservative legislators to ensure that only "basic" research and development, those activities that were not conducted by the private sector, received support. Federal aid was warranted only insofar as it helped determine the "feasibility, not the commercial application, of various processes." Support for all other research activities was "corporate welfare."[115] For Walker and his colleagues, hydrogen and the latest nuclear reactors were worthy of support; technologies harnessing wind, solar and geothermal energy were not.[116] Walker's articulation of the advantages of hydrogen was couched almost entirely in terms of its political attractiveness to industry. Importantly, he suggested that hydrogen was a primary energy resource in and of itself, as opposed to an energy carrier/chemical fuel that cost energy to produce from a primary energy resource. This was a crucial distinction Walker and like-minded hydrogen boosters tended to elide.

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[114] House Committee on Science, *Fuel Cells: The Key to Energy Independence?* 107th Congress, 2d sess., 24 June 2002, Serial No. 107-83, 8.

[115] *Congressional Quarterly Almanac*, Volume LI, 1995, 104th Congress, 1st sess. (Washington, D.C.: Congressional Quarterly Inc., 1996), 5-29.

[116] Walker's voting record was consistently against renewable energy research and for large capital-intensive projects. He strongly supported HR 655, which called for $100 million in spending authority on hydrogen over three years in order to enable the private sector to demonstrate the feasibility of using it for industrial, residential, transportation and other applications by 2000. The bill also capped research funding for other energy supply research program including fossil, solar and fusion (*Congressional Quarterly Almanac*, Volume LI, 1995, 5-29). During negotiations for energy and water appropriations for Fiscal Year 1996, Walker and John T. Myers (Republican of Indiana) drafted a bill that proposed to slash funding for solar and renewable energy from $388 million in Fiscal Year 1995 to $202 million, eliminating research into water-generated power, international solar research and solar building research (*CQA* vol LI, 11-36). During negotiations in the Republican-dominated House in 1996 over the energy and water development appropriations bill (HR 3816), a bill that cut $143 million from the Clinton Administration's request for $363 million for renewable energy programs, Walker

Retiring from Congress in 1997, Walker remained influential in Washington as chairman of the Wexler-Walker lobby firm and played an important role in shaping Republican energy policy. In 2000, he joined the presidential campaign of George W. Bush as head of its Space, Science and Technology Task Force. In the fall, Walker delivered a speech at an international symposium on automotive technology extolling hydrogen's attractions in a "public policy sense." While fossil fuel supplies were declining, he claimed, hydrogen was "inexhaustible." It had been successfully used in spacecraft and its environmental benefits were undeniable. Unfortunately, said Walker, the Clinton administration had done little to advance hydrogen technology. But times were changing. Hydrogen vehicles, claimed Walker, were the solution to the social problems facing the automobile industry, particularly environmental activism. The technology would ease political pressure for the expansion of mass transit, putting Detroit's "most virulent critics on the defensive" and assuring the automobile industry's viability for years to come.[117] In short, although Walker

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voted against efforts to cut $17 million from the so-called Advanced Light Water Reactor. He then voted unsuccessfully against an amendment by Republican Representative Dan Schaefer (Colorado) to add $42.1 million for wind, solar and geothermal energy (*CQA*, vol. LII, 1996, H-116).

[117] Robert S. Walker, "Hydrogen is Regaining Its Status As an Alternative Fuel," adapted by the *Minneapolis Star-Tribune*, 4 October 2000, from Walker's speech in Dublin, Ireland at the International Symposium on Automotive Technology and Automation; http://www.wexlerwalker.com/hydrogen.htm, accessed 23 March 2006. Walker's speech, a virtual manifesto of the political uses of hydrogen, corresponded well with the activities of his lobbying firm. One of its specialties was guiding industry through the shoals of environmental and product regulation

worked to retard the development of renewable energy technologies in Congress and supported the nuclear and petroleum industries, he also claimed environmental credentials through his support of hydrogen.[118]

This strategy was adopted by the administration of George W. Bush. In January 2002, it cancelled the PNGV in favour of a new program called FreedomCAR (Cooperative Automotive Research).[119] A $500 million joint effort between the Department of Energy and the auto industry, FreedomCAR was designed to enable development of hydrogen fuel cell automobiles. Energy Secretary Spencer Abraham used the occasion of Detroit's annual North American International Auto Show to inaugurate the program. In the presence of General Motors Chairman Jack Smith and the "Autonomy," a non-functioning model of the company's latest futuristic hydrogen fuel cell concept vehicle, Abraham announced plans to develop a national hydrogen infrastructure to service the fleets of fuel cell electric vehicles that would, as the *New York Times* put it, eventually replace the internal combustion engine automobile.[120]

In its constitution, FreedomCAR was similar to the PNGV. Conceived as a substitute for new fuel efficiency legislation, it was an open-ended advanced power source technology program with ambitious goals. Woven into hopes for a hydrogen economy were the same long-standing political priorities of the automobile and

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legislation. It boasts of its track record of stopping "bad legislation in its tracks." The firm's client list in its "Environment and Energy-Related" category included Caterpillar, British Petroleum, General Motors and the Alliance of Automobile Manufacturers; http://www.wexlerwalker.com/environ.htm, accessed 23 March 2006.

[118] In 1994, Walker's work as a hydrogen lobbyist was recognized by the National Hydrogen Association, an industry trade association formed by automakers, fuel cell developers and chemical concerns in 1989.

[119] U.S. Department of Energy, FreedomCAR and Fuel Partnership Plan, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf, accessed 22 February 2007.

[120] Neela Banerjee and Danny Hakim, "U.S. Ends Car Plan on Gas Efficiency; Looks to Fuel Cells," *The New York Times*, 9 January 2002, p. A1.

petroleum industries that had informed the PNGV. As an administration official admitted to the *New York Times*, the Department of Transport's proposals to tighten fuel efficiency would take so long to legislate that the fuel cell project would render them redundant.[121] One General Motors official was more explicit about the political uses of hydrogen and hydrogen fuel cells, remarking to *The Wall Street Journal* that FreedomCAR would serve as "ammunition" in the auto industry's fight against environmentalists and their campaign for tougher CAFE standards.[122] This echoed Walker's stated strategy.

FreedomCAR was only the opening act in the government's hydrogen turn. In January 2003, George W. Bush used the occasion of the state of the union address to announce the Hydrogen Fuel Initiative (HFI), the infrastructure portion of the fuel cell automobile program. Bush dwelt on the miracle qualities of hydrogen, recalling the rhetoric of the hydrogen futurists of the early 1970s. In powering the fuel cell automobile of the future, he said, hydrogen would solve the foreign policy, economic and environmental problems that came with the nation's dependence on fossil fuel. To this end, the administration would devote $1.2 billion for research over five years.[123]

The Hydrogen Fuel Initiative was very ambitious. The plan hinged on developing fuel cells 2.5 times more efficient than "improved" gasoline engine, allowing the United States to continue to expand its light duty fleet, maintaining "our transportation freedoms," as the Department of Energy's chief of Energy Efficiency and Renewable Energy David Garman put it, while reducing emissions.[124] In 2003, the 200 million light duty vehicles in the United States consumed 7.78 million barrels of oil per day and 2.84 billion barrels per year, the equivalent of 160.5 million tons of hydrogen. Actual annual hydrogen production was then about nine million tons. The Department of Energy projected that by 2040, U.S. oil consumption for light duty transportation would more than double to 18.3 million barrels per day and 6.68 billion barrels per year, amounting to 377.6 million tons of hydrogen.[125] Because the Department of Energy assumed that the fuel efficiency of gasoline engines would improve by an unknown degree by 2040, its calculations implied a massive expansion of the light duty fleet. If, however, this petroleum was converted to hydrogen and run in advanced fuel cell automobiles, claimed the federal government, this would lower the amount of hydrogen required to 150 million tons, the equivalent of 2.67 billion barrels of oil, or about 7.31 million barrels per day. This would save about 11 million barrels of projected oil consumption per day, reducing daily consumption below the 2003 level by about 500,000 barrels.[126]

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[121] David Ludlum, "Fuel Cell Companies Offer Choice and Risk," *The New York Times*, 23 December 2001, p. BU9.

[122] Jeffrey Ball, "Bush Shifts Gears on Car-Research Priority," *The Wall Street Journal*, 9 January 2002, p. C14.

[123] George W. Bush, 28 January 2003, http://www.whitehouse.gov/news/releases/2003/01/20030128-19.html.

To be sure, there were serious technological and material-physical limitations to this plan, particularly the supply of platinum. Though the HFI represented an unprecedented commitment to hydrogen infrastructure technologies, politicians, analysts and industry officials agreed that much greater investment was needed to realize its stated objectives. Hearings held by the House Science Committee in March 2003 laid bare the issues at stake. Only $700 million of the HFI consisted of new money, the rest having being reallocated from existing programs, including renewable energy. Princeton energy systems analyst Joan Ogden estimated that a system supporting 100 million vehicles could cost between $50 billion and $100 billion. Donald Huberts, Shell's chief of hydrogen operations, stated that $20 billion would be needed to supply two per cent of the U.S. automobile fleet with hydrogen by 2020, and hundreds of billions thereafter.[127]

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[124] House Committee on Science, *The Path to a Hydrogen Economy: Hearing Before the Committee on Science*, 108th Congress, 1st sess., 5 March 2003, Serial No. 108-4, 23.

[125] U.S. Department of Energy, *Basic Research Needs for the Hydrogen Economy: Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use*, 13-15 May 2003, 11; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "FreedomCAR and Fuel Partnership," March 2006, 2 http://www.1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf, accessed 22 February 2007.

[126] U.S. Department of Energy, *Basic Research Needs for the Hydrogen Economy*, May 2003, 11; House Committee on Science, 5 March 2003, 43.

What was more, government and industry had a selective understanding of the nature of technological progress. Though improvements in internal combustion engine performance had historically outpaced those in batteries and fuel cells, the federal government predicted a dramatic reversal of this trend by 2040. The Department of Energy and industry professed to see no short-term potential in heat engine technology. In 2002, General Motors chief executive Rick Wagoner stated that engineers had "wrung the towel" on the gasoline engine, a position shared by the EERE's Garman.[128] This contrasted with Garman's faith in the hydrogen fuel cell automotive project, where one major reverse salient in the on-board hydrocarbon reformer had been exchanged for several others in on-board vehicle hydrogen storage and a hydrogen infrastructure.[129] In fact, this position was undermined by the Department of Energy's calculations of projected energy consumption for transportation in the year 2040. These posited progress in the performance of both fuel cells and internal combustion engines, for the formula was based on fuel cells more than twice as efficient as *improved* gasoline engines.

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[127] House Committee on Science, 5 March 2003, 144-149.

[128] Dan Baum, "GM's Billion-Dollar Bet," *Wired* 10, August 2002, http://www.wired.com/wired/archive/10.08/fuelcellcars_pr.html, accessed April 15 2006.

[129] House Committee on Science, 5 March 2003, 21.

The contradictions between free market ideology, government commitment to the hydrogen economy, the state of the technological art and public expectations were apparent in the testimony of Alan C. Lloyd, chair of the California Fuel Cell Partnership, during the House Committee on Science hearing. Lloyd wanted the federal government to stimulate the market for fuel cell vehicles by purchasing them for use in its own fleets. Ultimately, he stated, industry had to build something the public would be willing to buy. Garman agreed. Automotive fuel cell technology first had to be made affordable and reliable before questions of infrastructure could even be discussed.[130]

By the early 2000s, however, researchers had not made the hydrogen fuel cell electric automobile as cheap and dependable as the gasoline automobile. Despite Ballard's success in improving power output in the 1990s, fuel cell automobiles faced a host of issues relating to cost, durability and range. One major reverse salient Ballard researchers encountered in the proton exchange membrane fuel cell during an advanced phase of engineering research illustrated the effects of the automotive duty cycle on fuel cell chemistry. They discovered that when the fuel cell power unit was not drawing hydrogen, a condition known as "fuel starvation," it would emit carbon dioxide. Researchers subsequently learned that in the absence of hydrogen, the platinum catalyst was oxidizing the carbon support structure on which it was mounted. This resulted in the slow degradation of the electrode, loss of active catalytic surface area and decrease in performance.[131] Fuel starvation is a regular occurrence in the daily stop-and-go operation of fuel cell automobiles: unlike internal combustion engines, fuel cells do not "idle" and thus do not draw fuel when a vehicle powered by them is at rest.

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[130] Ibid., 146-147.

By the early-mid 2000s, fully integrated automotive fuel cell systems cost between $4000-$5000 per kilowatt, far from the Department of Energy objective of $35-$45 per kilowatt. In 2004, polymer ion-exchange membrane cost about $200 per square meter. Ballard believed this would have to be reduced to $5-$7 per square meter to make commercialization possible. However, the company was caught in an economic conundrum resulting from its reliance on this specialized material, originally developed by Du Pont in the 1960s for the chlor-alkali chemical industry. Even if large numbers of fuel cell electric automobiles were ordered, the volume of required polymer material would still be far too small to entice the chemical industry to produce it in the quantities necessary to reduce costs. Paradoxically, the problem became worse as Ballard improved the performance of proton exchange membrane fuel cells. One of the ways this was accomplished was by making the membrane thinner, which reduced electrical resistance but also the overall volume of polymer material needed to build fuel cells.[132]

The durability of automotive fuel cells was another major problem. The lifetime benchmark for automotive fuel cells was 5000 hours, though less is known of actual lifetimes as fuel cell manufacturers have been more reticent about releasing such data than power output.[133] Finally, on-board hydrogen storage technology did not provide the minimum 480-kilometer range deemed by automakers to be the minimum acceptable to consumers. Because hydrogen has a small molecular diameter, it is prone to leakage from containment vessels, meaning they must be built to exacting standards. By the early 2000s, compression was the most mature of all hydrogen storage technologies but because hydrogen has much less energy density than carbonaceous fuels, this offered limited range. For example, 3600 pound per square inch storage, the standard in the late 1990s, provided fuel cell electric demonstration vehicles with ranges of between 160 kilometers (Ford Focus FCV) to 250 kilometers (NECAR II). Liquid hydrogen storage gave more energy capacity and, on paper, longer range (NECAR IV, 450 kilometers) but it cost energy to liquefy hydrogen. Liquid hydrogen also rapidly "boils off" or evaporates through containment materials, resulting in considerable wastage. The advent of 5000 psi compression storage in the mid-2000s gave ranges of between 145 kilometers (DaimlerChrysler F-Cell) and 355 kilometers (Honda FCX), still well short of the 480 kilometer benchmark.[134]

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[131] Charles Stone, "Future Energy Sources," First Annual Society of Chemical Industry-Chemical Heritage Foundation Innovation Day, Philadelphia, PA, 14 September 2004.

[132] Ibid.

Despite these technological hurdles, the purpose of the CAFCP was to build public expectations of the imminent commercialization of a hydrogen fuel cell vehicle with the cost-effectiveness of a gasoline automobile. Lloyd saw the California Fuel Cell Partnership, comprising 26 hydrogen fuel cell vehicles and seven refueling stations by

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[133] The National Research Council-National Academy of Engineering suggested the 5000-hour standard had not been demonstrated under realistic operating conditions as of 2004; National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, 26.

[134] Rebecca L. Busby, *Hydrogen and Fuel Cells: A Comprehensive Guide* (Tulsa, OK: PennWell, 2005), 256-260. In comparison, the makers of the most advanced battery electric vehicles of the early 2000s claimed ranges of as high as 190 kilometres (Honda EV Plus, Nissan Altra EV) to 200 kilometers (Toyota RAV 4); Westbrook, *The Electric Car*, 133. Some effort has been devoted to developing metal hydrides, metallic structures that store hydrogen, but these technologies are very heavy and require energy to release the hydrogen; DeCicco, *Fuel Cell Vehicles*, 64.

2002, as a means of introducing as many people as possible to the physical reality of a fuel cell automobile and cultivating a "mindset" that such zero-emission vehicles could be pressed into service immediately. This, he said, would show that California was duly executing its policy of a technological solution to the problem of air quality. All that was needed to launch this revolution, said Lloyd, was to give the public a "vision" that they would find irresistible.[135]

Without a hydrogen infrastructure, however, such a vision could not be realized. Despite investing hundreds of million of dollars in hydrogen and hydrogen fuel cell research since the early 1990s, the federal government had given little indication by the mid-2000s that it was prepared to subsidize the construction of such a refueling network. With the costs of automotive fuel cell power remaining stubbornly high, DaimlerChrysler and the American automakers indefinitely postponed their plans to introduce commercial fuel cell electric passenger automobiles by 2004.

The conflicting interests of the auto industry, the federal government and the maker of automotive fuel cells were reflected though the vicissitudes of Ballard's market capitalization. Its stock stood at CDN $100 at the end of 1997 and rose to $188 in early 1998, before being split three for one. The price declined briefly during the financial crisis in Asia and Russia in the summer of 1998 before rising dramatically to $160 in early 2000. Ballard's share price did not dip below $100 for the rest of the year.[136] By late 2000, however, the company's stock was fluctuating wildly, mainly on word in December that the CARB was weakening its 10 per cent ZEV quota for 2003. News that the regulatory agency would maintain this standard led to a brief rally, but also revealed that investment in Ballard was based almost wholly on expectations for automobile commercialization, which were in turn dependent on state and federal politics. By April 2001, Ballard shares had lost 68 per cent of their value from their 52-week high. With investors no longer willing to invest in "equity offerings" and with the automotive program in serious doubt, Ballard began promoting its line of stationary utility fuel cells.[137] By late 2001, industry analysts were increasingly speaking of this as the first commercial fuel cell application.[138]

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[135] House Committee on Science, 5 March 2003 54-56, 68-69, 78, 179-180.

[136] Jason Kirby, "It's a Tough Sell: Having Survived the Hype About Fuel Cells Replacing the Internal Combustion Engine, Ballard Turns To Other Markets," *Financial Post*, 18 March 2006, p. FP 1.

Ballard's partnership with DaimlerChrysler and Ford can best be described as an asymmetrical symbiosis. On the one hand, Ballard fuel cells allowed the automakers to mount a credible defense that they were actively engaged in developing a commercial zero emission vehicle after they ended their limited production runs of battery electric passenger vehicles. In turn, for a decade they had been Ballard's largest investors and biggest customers for fuel cell powerpacks for their demonstration vehicles, vaulting the company to world prominence in the process. On the other hand, DaimlerChrysler and Ford had joined other automakers in spending millions lobbying the CARB to roll back ZEV quotas, contributing to Ballard's crisis of expectations.

By the mid-2000s, most automakers seemed content to supply small numbers of pre-commercial prototype fuel cell electric vehicles for trials with individual customers and large demonstration projects like the CAFCP.[139] Only Honda remained committed to commercializing the technology. Using Ballard-built fuel cells, the FCX became the first fuel cell automobile to receive government certification as a zero-emission vehicle in 2002.[140] However, cost and infrastructure remain perennial challenges. With copies running well over $500,000, Honda must heavily subsidize the FCX project, offering the vehicle only for lease at preferential rates to select customers in the few regions where a rudimentary hydrogen refueling system exists, mainly in California.[141] Without major intervention by the federal government, the FCX, like other fuel cell demonstration vehicles, seems destined to remain an expensive symbol of green technological virtuosity rather than a serious commercial ZEV.

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[137] Richard Littlemore, "Hydrogen Bombs Out: Many Investors Who Thought Ballard Power's Fuel Cell Technology Was a Miracle Last Year Have Lately Been Bailing Out," *National Post Business*, April 2001, p.54.

[138] David Ludlum, "Fuel Cell Companies Offer Choice and Risk," *The New York Times*, 23 December 2001, p. BU9.

The reasons commercial fuel cell automobiles did not appear in 2004 have to do more with political than with "objective" economic or technological factors. The construction of some tens of thousands of platinum-using membrane fuel cell electric automobiles, or larger numbers of alkaline fuel cell automobiles, and an attendant hydrogen infrastructure, is technically feasible and perhaps even affordable in the sense that expectations for technological performance are always relative. Historically speaking, government intervention has played an indispensable role in the construction of large energy and transportation systems. It is doubtful, however, both that these automobiles could provide the same level of performance, reliability and cost-effectiveness as advanced gasoline vehicles and that fleets of such vehicles would be the most efficient way of transferring primary energy for use in an automobile, at least in the foreseeable future. That users of fuel cell vehicles would have to moderate expectations of durability, comfort, cost and convenience conditioned through experience with the internal combustion engine automobile is no argument, however, that some kind of hydrogen fuel cell-based transportation and energy system could not be built. In the mid-2000s, it was simply not in the interests of industrial and political elites to do so.

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[139] These include DaimlerChrysler's F-cell, of which some 60 have been built, and Ford's Focus FCV, both of which are powered by Ballard fuel cells. As of 2005, the CAFCP had trialed some 55 fuel cell automobiles and buses. The infrastructure portion of California's fuel cell experiment, the so-called "Hydrogen Highway," had 11 stations, with plans for up to 200 by 2010; Busby, *Hydrogen and Fuel Cells*, 139, 257-258.

[140] Press release, "Honda Fuel Cell Vehicle First To Receive Certification; Honda FCX Slated for Commercial Use," 24 July 2002, world.honda.com/news/2002/printerfriendly/4020724.html., accessed 11 December 2006.

[141] James R. Healey, "Honda FXC: Ride Pollution-free," *USA Today*, 17 November 2005, *Test Drive*, usatoday.com, accessed 11 December 2006.

Conclusion - The Efficient Abundant Energy Machine

To some observers, FreedomCAR and the Hydrogen Fuel Initiative were essentially political ploys to stall near-term efforts to improve fuel efficiency. The *Wall Street Journal*'s Jeffrey Ball called the programs a "futuristic technological crusade" that automakers hoped would "win them green points" in Washington in the battle against CAFE.[1] But support and opposition for hydrogen fuel cells has not fallen along partisan ideological lines. Leading opponents of CAFE like Democratic Senator of Michigan Carl Levin emulated the auto industry in balancing the fight against legislated fuel efficiency with support for fuel cells as a clean energy option.[2] Democrats like Connecticut Senator Joseph Lieberman were not opposed to the idea of a hydrogen economy but rather the Bush administration's shallow commitment to it. North Dakota Senator Byron Dorgan called for an "Apollo" type program with better funding and clearer milestones.[3]

Environmentalists had similar views. While they roundly condemned the Bush program as an excuse to put off immediate action on emissions, they opposed the means by which the administration proposed to make hydrogen, not hydrogen technologies per se. Greenpeace and the National Resources Defense Committee favored renewable hydrogen, attacking the administration's plan to make hydrogen from hydrocarbons and possibly nuclear power.[4]

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[1] Jeffrey Ball, "Evasive Maneuvers: Detroit Again Tries to Dodge Pressures For a 'Greener" Fleet; Oil Fears Since September 11 Add Urgency to Latest Round of Gas-Mileage Politics; 'Supercars' and Fuel Cells," *The Wall Street Journal*, 28 January 2002, p.A1.

[2] Carl Levin, press release, "Senate Passes Levin-Bond Amendment on Fuel Economy Standards: Bipartisan Bill Aims to Improve Fuel Economy and Protect the Environment Without Harming the U.S. Manufacturing Industry," 13 March 2002, http://www.senate.gov/~levin/newsroom/release.cfm?id=209162, accessed 5 August 2006.

[3] "Bush Hydrogen Initiative Fuels Debate: Suddenly Hydrogen Is Center of Revived Energy Debate," 7 February 2003, CNN.com, accessed 5 August 2006.

The question of why ideologically diverse groups have become attracted to hydrogen and fuel cells is related to the problem that this dissertation posed at the outset, the reasons for the perennial appeal of these technologies despite the strangely consistent record of unfulfilled expectations. The fuel cell should be viewed in light of the deep-rooted beliefs about energy in American society.[5] George Basalla observes the persistence in Western but particularly American culture of energy myths, above all, the idea of the energy utopia, the notion that abundant energy is an objective condition of American society and a birthright. Americans have historically viewed single sources of primary energy as the basis of limitless wealth and progress. When these sources prove unable to meet expectations, hope is reinvested in new energy sources, which are exploited with similar results.[6] Energy historian James C. Williams notes that the American approach to energy technology stems from a high valuation on reliability and a willingness to expend energy to save time, leading to the development of centralized energy production systems that are extremely complex, expensive and vulnerable to breakdown.[7]

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[4] Natural Resources Defense Council press release, "White House Fuel Plan Ignores Today's Oil Insecurity," 6 February 2003, http://www.nrdc.org/bushrecord/articles/br_1254.asp, accessed 15 April 2006; Greenpeace press release, "Greenpeace Calls for a Clean Hydrogen Initiative," 5 February 2003, http://www.greenpeace.org/usa/press/releases/greenpeace-calls-for-a-clean-h, accessed 5 August 2006.

[5] Martin V. Melosi, *Coping With Abundance: Energy and Environment in Industrial America* (Philadelphia: Temple University Press, 1985), 1-19.

[6] George Basalla, "Some Persistent Energy Myths," in *Energy and Transport: Historical Perspectives on Policy Issues* eds. George H. Daniels, Mark H. Rose (Beverly Hills, CA: Sage Publications, 1982), 27.

[7] James C. Williams, *Energy and the Making of Modern California* (Akron, OH: University of Akron Press, 1997), 5.

These tendencies blended into post-Second World War U.S. energy policy, one shaped largely by the experience of wartime atomic weapons development. As authors like Bruce Podobnik and Gijs Mom have observed, choice in American energy technologies has been largely shaped by military-industrial imperatives. Social progress was equated with technological progress, at the core of which was abundant energy. As John Byrne and Daniel Rich note, this was analogous to national security. The nuclear reactor was the instrumental means for ensuring national security, an "abundant energy machine" that brought with it a host of expectations of energy plenitude, economic prosperity and general social progress. Nuclear energy became the focal point of public energy policy, requiring a "techno-bureaucracy," a vast centralized research and development apparatus absorbing tens of billions of dollars and the creative energies of tens of thousands of people. This system was geared to satisfy high energy consumption, not consume energy efficiently.[8]

In some respects, the history of the fuel cell corresponds well with this paradigm. Fuel cells were first developed in the U.S. for military or quasi-military purposes, and research and development unfolded within the military techno-bureaucracy. Government agencies, particularly NASA, were prepared to spend considerable sums of money to build high performance fuel cells. The space agency's selection of the fuel cell for its human-carrying spacecraft encouraged ARPA's experimentation with the technology. The success of the aerospace fuel cell, achieved at great cost, provided the ideological rationale and material basis for further technology development. NASA enabled Pratt & Whitney/United Aircraft/United Technologies to develop a fuel cell research, development and manufacturing base, positioning the company to dominate the nascent commercial fuel cell industry. During the 1970s, the federal government subsidized commercial fuel cell development, cementing the monopoly of United Technologies in the emerging commercial fuel cell business in the late 1980s. In this and subsequent efforts, the military and the energy bureaucracies of the federal government never completely abandoned their role as handmaidens to the commercial fuel cell.

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[8] John Byrne and Daniel Rich, "In Search of the Abundant Energy Machine," in *Energy Policy Studies: The Politics of Energy Research and Development*, vol. 3, eds. John Byrne and Daniel Rich (New Brunswick, NJ: Transaction Books, 1986), 151.

In subsequent years, changing socio-cultural and political conditions and advances in technology raised expectations such that efforts to develop the fuel cell became much more than simply a search for a superior power source. In the 1990s, automotive fuel cell programs became a quest for a new energy utopia. In these senses, fuel cell research and development corresponds well with Byrne and Rich's sociological category of the "abundant energy machine."

In other ways, the fuel cell's flexibility set it apart from other power source technologies. Depending on the fuel storage and supply system, a fuel cell can be configured in a number of ways. It can be made to serve as a reversible storage device, like a secondary battery, in which chemical reactants are combined to yield electricity and dissociated using electricity. This is most easily accomplished using pure hydrogen and oxygen. Researchers have also conceived the fuel cell as an "electrochemical engine," in which chemical fuels are combined in an irreversible reaction. Like photovoltaic arrays and, to an extent, conventional galvanic batteries, fuel cells are scalable. Their efficiency is unrelated to their size; thus, fuel cells may theoretically be used in a much broader range of applications than internal combustion engines and nuclear reactors, from the tens of watts to tens of millions of watts. Engineers have tried to substitute fuel cells for conventional batteries in portable electronic devices, automobiles, spacecraft and portable and stationary internal combustion generators.

Researchers have long seen the fuel cell not only as an abundant energy machine but also as a frugal energy machine, an efficient energy technology. This perception was reinforced by the ways in which researchers tested fuel cells. Like other technologists, fuel cell researchers wanted unambiguous results and total control over "potential disturbing factors." The resulting tests replicated conditions unlike those commercial fuel cells encountered in real-world applications, allowing inferences or "similarity judgments" to be drawn between certain artifacts and others in their "class."[9]

In the earliest phases of postwar fuel cell programs, research could be done quite cheaply in modestly-equipped laboratories. The Bacon program was sustained for years on an annual budget of only a few thousand pounds. The early years at Ballard were similarly lean. Even individual scaled-up stacks of fuel cells could be built and tested relatively inexpensively. It was in these early stages that expectations of expense, power and longevity of full-sized devices were raised. The formation of "similarity judgments" left researchers unprepared for the cost of making laboratory models into robust commercial power sources, particularly during the arduous process of engineering research. It was then that fuel cell development became a capital-intensive activity.

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[9] Trevor Pinch, "'Testing-One, Two, Three…Testing!'" Toward a Sociology of Testing," *Science, Technology & Human Values* 18, no.1 (winter 1993): 27-31; Donald MacKenzie, "From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy," in *The Uses of Experiment: Studies in the Natural Sciences*, eds. David Gooding, Trevor Pinch and Simon Schaffer (Cambridge: Cambridge University Press, 1989), 414-415.

As with other technologies, justifications for fuel cells changed as economic, political, cultural and environmental conditions have shifted. Faced with the Electrical Research Association's resistance to his invention as a reversible electrical storage device, Bacon agreed to reconfigure it as a "fuel cell." This semantic shift couched the technology as an electrochemical engine that used hydrogen not as an energy carrier, a medium for the storage of electricity, but as a "fuel" in the sense of combining chemical reactants in an irreversible reaction to produce electricity. The waste water byproduct was discarded rather than dissociated back into its constituent elements through electrolysis. The U.S. Army's failure to develop the fuel cell as a universal electrochemical engine replacing batteries and conventional heat engines led it to emphasize the fuel cell's quality of silent operation in soldier-portable radios.

By the late 1960s and early 1970s, increasing public concern with air and water pollution led marketers to focus on different qualities of the fuel cell. During the TARGET program, the gas utilities initially posited the fuel cell simply as a means to compete with the electrical utilities, arguing that distributed generation employing piped gas would be more efficient than centrally generated power transmitted by power lines. In the early 1970s, Pratt & Whitney and the gas and electric utilities appealed to popular dissatisfaction with large conventional power stations by more frequently citing those aspects of fuel cells that addressed quality of life issues, particularly clean emissions and scalability.

In the 1990s and early 2000s, fuel cell promotion reached the high point of sophistication. Promoters framed the automotive fuel cell as the ultimate power source, an efficient abundant energy machine. Because consumers would not compromise their lifestyles, claimed the technology boosters, the fuel cell automobile would allow them to satisfy their environmental consciences without relinquishing any of the convenience they had come to expect from internal combustion vehicles. Consumers could continue to drive in the style to which they had become accustomed and save the environment in the process. As the basis of a hydrogen economy, the fuel cell automobile became the latest utopian energy technology, promising environmentally sustainable power, prosperity and general social progress. With the indefinite postponement of this project in the mid-2000s, industry and governments exploited the rhetoric of hydrogen fuel cell technology, invoking utopian promises in order to placate increasing popular dissatisfaction with U.S. energy policy.

People have misconceived the fuel cell in two important ways. The first directly relates to the technology's operating principles. Unlike heat engines, which convert chemical to heat energy and thence to mechanical action, fuel cells directly convert chemical into electrical energy. As the electrochemist John Bockris has suggested, this has given rise to the idea that fuel cells somehow evade the second law of thermodynamics. In fact, says Bockris, heat engines and fuel cells utilize in different ways the same chemical reaction that results when two atoms of hydrogen and one atom of oxygen are combined to produce two molecules of water; heat engines use the kinetic action of hot molecules released in the reaction to produce mechanical work, while fuel cells release a stream of electrons to drive electric appliances. As such, energy is still consumed in the direct conversion of chemical to electrical energy.[10]

The second misconception stems from the reductive focus scientists and their sponsors have placed on the fuel cell energy converter itself. This has caused them to neglect the sources of primary energy that would supply the hydrogen. As Appleby and Foulkes have noted, the efficiency of fuel cells in relation to other power sources has always depended on how far back researchers have been willing to trace the energy transformation chain to primary energy resources: fossil, biomass and synthetic fuels and hydroelectric, wind solar and nuclear power.[11] This has been a task that fuel cell researchers and their sponsors have historically neglected. Projects have rarely been started on the basis of a comprehensive energy budget or cost-benefit analysis. For years, the dream of a hydrocarbon fuel cell that could be seamlessly integrated into the extant energy system allowed researchers to set aside these larger questions and concentrate on the fuel cell stack itself, despite the fact that sophisticated reformer technology was needed to convert hydrocarbons to hydrogen.

In both post-war booms, the great hope of a hydrocarbon fuel cell-based energy order fizzled in uncontrollable chemical side reactions, giving way to alternate fuel cell technologies that traded some areas of technical complexity for others. In the 1960s, planners believed the solution was hydrazine. In early 2000s, the hydrogen fuel cell was resurrected. This, however, begged complex questions of which primary energy sources would be converted to hydrogen and how much energy it would cost to do this. In short, planners had to consider not just the energy conversion unit, the fuel cell and hydrogen reformer, as with the hydrocarbon fuel cell, but a dizzying array of external factors. Commercializing the hydrogen fuel cell on a large scale implied the creation of whole new energy system, a hydrogen economy, with vast political, economic and cultural consequences that industry and government have hitherto been unprepared to directly address.

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[10] John O'M Bockris and Amulya K.N. Reddy, *Modern Electrochemistry 2B: Electrodics in Chemistry, Engineering, Biology and Environmental Science*, 2nd ed. (New York: Kluwer Academic/Plenum Publishers, 2000), 1801.

[11] A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), 179.

The history of fuel cell development also reveals the depth of the affinity for technological utopianism in American culture. That expectations have always outpaced the knowledge base derives directly from the notion of the fuel cell as a kind of shortcut around the laws of physics, a belief that accords well with the American understanding of progress as a series of technological fixes.[12] This idea has resonated deeply not only among the original military-industrial promoters of fuel cells, but throughout broad social strata that shared a common vision of limitless clean energy.

It is these theoretical qualities of high power, scalability, and silent, clean and efficient operation that have made the fuel cell a protean technology, all things to all people. A variety of interest groups with contrasting, sometimes conflicting, visions of society, have shaped the technology for their own purposes. Each has seen it as an instrumental means of creating an ideal socio-technical landscape. At different points in its history, the fuel cell has been conceived as a superior kind of battery, variously powering advanced communications and surveillance devices on the battlefield of the future, spacecraft, or, more recently, laptop computers. It could be a superior automobile power source, or it could facilitate distributed generation in places where the risk of big electrical stations was unacceptable. Some researchers have seen the fuel cell in its hydrocarbon forms as a way to make the fossil fuel system more sustainable. Others perceived a commercial hydrogen fuel cell as the vanguard of an energy revolution that would sweep away the old hydrocarbon order. For hydrogen futurists, the basis for this grand vision was either nuclear or "clean coal" power. For environmentalists, it was renewable hydrogen produced by solar or wind power.

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[12] Byrne, Rich, "In Search of the Abundant Energy Machine," 151.

What, then, is the legacy of fuel cell research and development? In one way, it may be read as an extreme case of the Hughsian reverse salient, the condition that describes the uneven growth of a large technological system, a concept outlined in the introduction.[13] In another sense, it represents the opposite, for the relative neglect of auxiliary systems such as fuel reformers, temperature, fuel and moisture controls and hydrogen storage by a succession of program managers in a succession of programs tended, more often than not, to inhibit the development of any kind of system at all, whether it be a "manpacked" radio or a network of fuel cell vehicles and their attendant fuel infrastructure. In the case of aerospace fuel cells, the one notable success in the early years, the fuel question could be compartmentalized within individual spacecraft and costs for the relative handful of short missions could be heavily subsidized.

Gijs Mom has observed that one effect of the long project to commercialize the battery electric vehicle is that its promoters have subjected existing automotive technology to serious scrutiny.[14] This may also be the case with fuel cell research and development. The difference is that attempts to find ways to make various kinds of fuel cell work in practically every known power source application have forced people to reconcile utopian expectations with the physical limitations of the entire energy and transportation system, as well as the power human relations that shape these technological networks.

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[13] Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: The Johns Hopkins University Press, 1983), 14.
[14] Gijs Mom, *The Electric Vehicle: Technology and Expectations In the Automobile Age* (Baltimore: The Johns Hopkins University Press, 2004), 301.

The lesson is that it is not the incumbent technological systems that are inflexible, unable to accommodate the fuel cell, but rather human values, rigid standards of performance and economy, that refuse to conform to the material realities of fuel cells. That so many fuel cell impresarios and researchers in the 1990s chose to ignore the experience of their predecessors, repeating many of the same elementary mistakes, is a testament to the enduring power of assumptions developed in reductive laboratory conditions and the importance of understanding history. In this sense, some of the latest hydrogen fuel cell research, development and demonstration projects have functioned as a *de facto* critique of the status quo in the manner of the classical literary utopias. They have provoked questions about the relationship between the ideal and the real, the nature of existing energy and transportations systems, the gap between expectations and the limits of sustainability and the origin of human values that give rise to dreams of endless economic growth, limitless energy and technological perfection.

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Appendix: Fuel Cell Types

Alkaline Fuel Cell (AFC): a fuel cell employing a liquid alkaline electrolyte, usually potassium hydroxide, and operating at around 200°C. This fuel cell employs hydroxyl anions, or negative ions, as the charge carrier, which move from cathode to anode. Alkaline fuel cells do not require platinum as the catalyst and can use nickel. Consequently, this type of fuel cell hardware is the cheapest of all fuel cell designs. Because the alkaline electrolyte solidifies when contaminated with carbon, these types of fuel cell must use costly pure hydrogen as fuel. The first practical fuel cell, the Bacon cell, was an alkaline design, as were the fuel cells used in the Apollo and Space Shuttle spacecraft, which were adaptations of the Bacon cell. Work on this type of technology has been superseded since the 1960s by other types of fuel cells.

Phosphoric Acid Fuel Cell (PAFC): a fuel cell employing an acidic electrolyte and operating at around 200°C. These fuels cells employ hydrogen cations, or positive ions, as the charge carrier, which move from anode to cathode. Acidic electrolytes have a degree of resistance to carbon, but such fuel cell systems require platinum as the catalyst. The phosphoric acid fuel cell design was the first to be commercialized. They are typically used in stationary utility applications and have been manufactured by United Technologies Corporation and the Japanese engineering firm Toshiba.

Proton Exchange Membrane Fuel Cell (PEMFC): a fuel cell employing a solid polymer electrolyte, typically acidic, and operating at around 85°C-90°C. The technology was originally developed by General Electric. Like PAFCs, acidic PEMs are cationic systems and require platinum. Further, the membrane itself is very costly. PEMFCs have the quickest power response of any fuel cell and are best for automotive applications. By the mid-2000s, a number of companies, most notably Ballard Power Systems, had built small numbers of pre-commercial PEMFCs.

Molten Carbonate Fuel Cell (MCFC): a fuel cell operating at around 650°C using a carbonate salt electrolyte. At operating temperature, the electrolyte becomes liquid and conducts anions from cathode to anode. This type of fuel cell uses high temperature to oxidize hydrogen and thus does not require platinum. It is also much more resistant to fuel impurities than lower temperature fuel cells. However, the high temperature and corrosive environment of the molten carbonate operating system leads to thermal expansion and electrolyte leakage, damaging lifetime. The long warm-up time of MCFCs make them best suited for stationary utility applications. MCFCs have been built and tested in small numbers since the 1950s by companies including Energy Conversion Limited, Texas Instruments and, more recently, M-C Power Corporation and Fuel Cell Energy.

Solid Oxide Fuel Cell (SOFC): a fuel cell employing a solid ceramic electrolyte at around 1000°C. Like the MCFC, the anionic SOFC relies on high temperature to oxidize hydrogen and so does not require precious metals and can tolerate dirty fuels. As with the MCFC, the high operating temperature of SOFCs creates problems of thermal expansion and restricts this class of fuel cell to stationary utility applications.

Many researchers have seen the SOFC as a possible replacement for PAFC and PEMFC types. A number of companies have investigated SOFC technology, most notably Westinghouse and Siemens Westinghouse. In 1999, the U.S. Department of Energy launched the Solid State Energy Conversion Alliance (SECA), a public/private partnership to explore SOFC technology.